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Visualising Lighting Simulations for Automotive Design Evaluations using Emerging Technologies

by

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Abstract

Automotive design visualisation is at a turning point with the commercial development of immersive technologies such as virtual reality, among other displays and visual interfaces. A fundamental objective of this research is to assess how seamlessly the integration of emerging visualisation technologies can be implemented into the new product development methodologies, with the use of lighting simulation, design review applications and the use of immersive hardware and software. Optical automotive considerations such as display legibility, veiling glare, and perceived quality among other current processes of Systemic Optical Failure (SOF) modes are analysed, to determine how the application of new immersive visualisation technologies could improve the efficiency of new product development, in particular reducing time and cost in early stages while improving decision making and quality.

Different hardware and software combinations were investigated in terms of their ability to realistically represent design intent. Following on from this investigation, a user study was carried out with subjects from various automotive engineering disciplines, to evaluate a range of potential solutions. Recommendations are then made as to how these solutions could be deployed within the automotive new product development process to deliver maximum value.

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List of Acronyms

AL	Ambient lighting
AMOLED	Active-matrix organic light-emitting diode
ANOVA	Analysis of variance
AR	Augmented reality
BRDF	Bidirectional reflectance distribution function
CAD	Computer aided design
CAE	Computer aided engineering
CCT	Correlated colour temperature
CIE	Commission Internationale de l'Eclairage
CIM	Computer integrated manufacturing
CPU	Central processing unit
CRI	Colour rendering index
DLO	Daylight opening
DMAIC	Define, measure, analyse, improve and control
DVM	Design verification method
EDM	Engineering data management
ERP	Enterprise resource planning
FMEA	Failure Mode and Effect Analysis
FOP	Face optical properties
GDEC	Gaydon Design and Engineering Centre
GPU	Graphics processing unit
HDR	High dynamic range
HDRI	High dynamic range imaging
HLDF	High level display front
HMI	Human-machine interface
HMD	Head mounted display
HPC	High-performance computing
HUD	Head up display
HVS	Human visual system
IMU	Inertial measurement unit
IP	Instrument panel
ISF	Innovation system foresight
JLR	Jaguar Land Rover
JND	Just-noticeable difference
MR	Mixed reality
NPD	New product development
OCAE	Optical Computer Assisted Engineering
OEM	Original equipment manufacturer
OFM	Optical failure mode
OD	Optical density
PDM	Product data management

PDT	Problem definition template
PET	Product Evaluation Technologies
PJND	Perceived just noticeable difference
PLM	Product lifecycle management
PCDS	Product creation delivery system
PQ	Perceived quality
PRD	Perfect reflecting diffuser
RGB	Red, green and blue
R&D	Research & development
SE	Systems engineering
SoC	System on chip
SOF	Systemic optical failure
SOP	Surface optical properties
SPD	Spectral power distribution
SW	Switch gear
TCQ	Time-cost-quality
TDI	Transport Design International
TPQ	Technical perceived quality
TRL	Technology readiness levels
UI	User interface
USP	Unique selling point
VIC	Virtual Innovation Centre
VLR	Very Light Rail
VOP	Volume optical properties
WMCA	West Midlands Combined Authority

Mathematical and light units

Cd	Candela
Cd/m^2	Candela per square metre
E	Illuminance
E$_e$	Irradiance
F	Luminous flux
I	Luminous intensity
I$_e$	Radiant intensity
L	Luminance
Lm	Lumen
Lx	Lux
L$_e$	Radiance
Nm	Nanometres
R	Reflectance factor
Sr	Steradian
W	watts
α	Absorptance
φ	Radiant flux
ρ	Reflectance
τ	Transmittance
ω	Solid angle

Declaration

I confirm that this thesis has not been submitted for a degree at another university and that all material is the original work of the author.

1 Introduction

The implementation of novel technologies in today's automotive industry is critical to deliver high quality products using state of the art features. At the same time, technology is the power source to optimise time-to-market and resource usage improvement in the new product development (NPD) process. From the product conceptualisation to the customer satisfaction, technology is without a doubt a paradigm shifter in the way we live and interact with everyday products and environments. Visualisation, in its current state is experiencing a technical breakthrough with the commercial introduction of immersive technologies such as virtual (VR) and augmented reality (AR), better displays and visual aids. By the other hand, simulation software is improving in a fast pace and is an essential tool to achieve more accurate design evaluations, which enables decision makers to take knowledgeable decisions earlier in the design phase, without the need for physical tests, while using resources more efficiently, resulting in a considerable time, cost and quality (TCQ) improvement.

The trade-off of implementing state of the art technology and digital design, rather than physical, has been proven to deliver better and faster results in the NPD process (Santos, et al. 2017). Lighting simulations had been part of this digital revolution, but there are still great advances to be made in the research and implementation of these kinds of technique. As technology takes giant leaps, development methodologies not only have to be updated, but should be able foresee and anticipate the next possible scenarios. So far virtual prototyping has proven to reduce time to market and product development expenditure by reducing the amount of physical evaluations, while increasing the accuracy of components (Abdel-Dader and Yu-Ching Lin 2009).

In the same manner, the aim of this research is to improve automotive visualisation and optical analysis, leading to quicker and more precise decision-making, and develop flexible methodologies, which deliver the most value for current and upcoming visualisation technologies. The use of these emerging tools plays a critical role in achieving better results, communication and

evaluation, transforming this task in a more agile and immersive experience, where replicating a realistic situation such as the lighting effects towards the user becomes critical.

This research is developed in collaboration with Jaguar Land Rover (JLR) at Gaydon site, working closely with the visualisation and optical analysis teams, while developing and testing new solutions at WMG's Product Evaluation Technologies research group. JLR's inter-attribute optical analysis team, currently works on various failure modes, which aim to ensure the product optical characteristics comply with specification and performance. These optical characteristics include a wide range of considerations which go from *interior colour harmony,* to more elaborate and specific issues such as *veiling glare* and *mismatch in lighting performance related to environmental conditions*.

New technology implementation is evidently of the utmost importance in scenarios where the latest technical advances are being tested and put into practice; moreover, it is indispensable in a fierce, fast paced industry where being the first competitor to provide the latest engineering solutions becomes an ever-growing challenge.

In this sense, automotive visualisation represents a complex task to express and communicate, considering the various variables involved, such as reflections, display legibility or perceived quality. In addition, optical design methodologies, should have the flexibility and adaptability to keep up with the new technology requirements, automotive legislation and anticipate solutions of upcoming trends like head-up displays (HUD's).

As a final stage, technology and change management will be considered as part of an end-to-end solution to optimise resources, time and quality through a product development value proposition based on visualisation.

Today, a great development in immersive visualisation technologies is taking place such as VR and AR which are positioning as the most heavily invested technology ventures for the years to come, projected to generate $120 billion (USD) by 2020, from which $90 billion comes only from

augmented reality (Digi-Capital, Augmented / Virtual Reality Report Q2 2016. 2016), including hardware, software and content.

In the automotive industry there has been a clear interest in applying these technologies for several years already. From 3-D CAD for virtual design, to the use of immersive and interactive or dynamic simulation, virtual environments are increasingly gaining terrain over traditional user interaction interfaces for its reach and viability.

The research, being visual in nature, intends to provide as many visual examples as it is possible in a printed document. For a more in-depth experience, digital links will be provided.

2 Defining the challenge. Automotive Visualisation Considerations

In order to have a comprehensive perspective, it is essential to review the most relevant concepts and milestones surrounding the development of lighting analysis and simulation as an NPD tool. It is important to make present and acknowledge the importance of these concepts, since they stand as the very basis of the optical analysis. In order to propose an advanced methodology of lighting simulation, first it is essential to have a concise rundown of the optical foundation, and subsequently, implement emergent visualisation technologies to properly evaluate light performance and user interaction.

These principles will determine parameters for the user's well-being, which can affect the mental perception of space or environment in a given moment (Hsiao, et al. 2014). Colour temperature, hue, luminance or illuminance among many others, can determine an optimal performance in a design feature, and a comfortable or deficient experience for the final user.

2.1 Lighting Simulation and Visualisation Packages

Throughout the NPD milestones and departments, there are many specialised digital simulation tools used for different purposes depending on the desired output, ranging from game driving simulation to real-time raytracing. These software packages have proven to be reliable to a great extent (Sissoko, et al. 2018), that fewer physical tests are needed to improve time/cost/quality (Lawson, Salanitri and Waterfield 2015).

There are studies which compare real life scenarios with the simulation results from almost 20 years ago already (Yan-Yung NG, et al. 2001) . From music venues to architectural sites, simulation results show to be convincingly close to real life measurements, so there is a good level of reliability for simulation data. But so far it has been either about the spread sheet and graphs about the figures

or an approximate image representation, photo-realistically produced if possible, which not necessarily shows the real numbers of the physical sample.

It is no different when it comes to automotive lighting simulations, where there is a need to replicate with meticulous accuracy a real-world scenario, textures, materials and lighting interaction with the user and its surroundings.

Today, Ansys Speos is the only optical and lighting simulations software to hold the C.I.E. certification. Other tools such as Theia and VRED are specifically used to visualise the optical analysis results and allow to set different light and conditions previously prepared for a review. These reviews can be displayed on a regular screen or in a VR environment.

The AR/VR integration is still in development, but this research aims to anticipate its application and structure to the future accessibility of these technologies. Lighting simulation uses optical and lighting parameters, to predict without a physical prototype possible design flaws and light performance. From artificial sources such as light bulbs and high intensity discharge (HID) headlamps, to natural skies, the interaction between the emitting source, environment light propagation and sensor sensitivity can be measured (Delacour, et al. 2002). Today the use of game engines such as Unity, Unreal are coming closer to replicating simulation using more powerful GPUs and AI algorithms, make possible the creation of these applications, while new interfaces are starting to emerge commercially (Nvidia corp. 2020).

Autodesk V-RED already supports the main VR headsets such as HTC-Vive, Oculus or Varjo , which make collaboration and design review a more engaging experience and capable in terms of collaboration (Autodesk, Setting up a scene in VRED with HTC Vive 2016), and these are precisely the scenarios where the research will implement more efficient product development methodologies based on visualisation technologies.

2.2 Perceived Quality in New Product Development

JLR, being in the premium automotive segment, is highly focused on delivering "zero-defect" high quality products to go beyond the customer's requirements. Therefore, Perceived Quality (PQ) is a high priority topic that goes beyond functionality and engineering itself. To fulfil this objective, from early product development stages, these customer requirements are translated into technical specifications (Stylidis, Rossi, et al. 2016) with the highest accuracy, to reduce to a minimum, failures in prototype iterations and prepare a smooth transition to the manufacturing phase. However, the need of achieving high accuracy levels in many design and development stages, has led to match perceived quality to an engineering level, which no longer focuses on aesthetics, consumer surveys and applied psychology (Stylidis, Rossi, et al. 2016). In this sense, further from socio-cultural segmentation (Petitot, et al. 2009), quality needs to be measured to later be applied into high technical quality.

JLR optical inter-attribute is currently focused on HMI performance analysis, but the visualisation reach may get to areas such as geometrical variation and impact on product experience (Forslund, et. Al 2013), where the customer expectations and needs are a main concern which need to be accurately identified and targeted from the engineering requirement process (Stylidis, Rossi, et al. 2016), and can be greatly enhanced by other disciplines such as analytical product design where marketing, policy and standard environments are also considered along with the engineering specification and requirements to finally build a design decision model framework (Frischknecht, et al. 2009).

While the craftsmanship has been regularly measured in a quantitative manner using different tools such as multidimensional scaling, cluster analysis and decomposition (Hossoy, et al. 2004), there is a need of applying an engineering quality framework to exchange subjective information, for more precise parameters from the attribute characteristics to the manufacturing translation.

A useful PQ definition and terminology (Stylidis, et. al 2015) called Technical Perceived Quality (TPQ), deals with the perceived quality attributes from an engineering perspective, and is divided into 4 main groups: Visual Quality, Feel Quality, Sound Quality and Smell Quality with other subdivisions seen in *figure 1.*
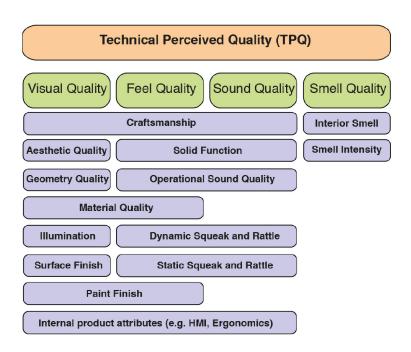
Figure 1. Illustration of the proposed conceptual terminology framework of the technical perceived quality in the automotive industry by Stylidis, et.al.

At this point, a design for manufacturing perspective has to be implemented from the first approved industrial design concepts in order to anticipate and attend issues related to the NPD process, customer's quality perception and design maturity (Forslund, et. al 2009). In the visual quality group, there are 8 subdivisions in which we can find: craftsmanship, aesthetic quality, geometry quality, material quality, illumination, surface finish, paint finish and internal product attributes such as HMI and ergonomics. All of them are measurable according to the manufacturing process, except perhaps, the aesthetic quality, since it can be given a subjective connotation, but if the aesthetical subgroup is analysed with engineering metrics, a better manufacturing insight can be targeted to achieve those results. Soon, design and engineering teams will benefit in such a great

extent by this concept, that specialised virtual laboratories will become the most important gears in the development phases. In this sense, the first step is to bridge a terminology of common language for aesthetic and engineering terms, to create a value Based Perceived Quality (Stylidis, et. al 2015), where ratings are allocated. As in qualitative studies, such as customer satisfaction, a rating system is set, to allocate values to intangible characteristics, such as appeal or emotions.

2.3   In-vehicle Visualisation Interfaces and Displays

Visualisation is pursuing new paradigms in the way we experience data communication and collaboration, whether it is a virtual review session with many people located in different places or by simply reviewing a design in a high-resolution display in high dynamic range (HDR), which is closer to the human visual system (HVS), due to the fact that reproduces a greater ratio of high and low tonal value and luminance. Compared to the human eye, these characteristics emulate the eye adaptation to scotopic, mesopic and photopic vision, capturing details within these ranges. As technology evolves and the technology and market readiness level increases, it starts to appear with more frequency in high-end displays, with higher contrasts and scaled chromaticity that delivers a more detailed picture and experience (Goncalves, et al. 2013).

In this sense, from the engineering side, automotive lighting simulations enable designers to predict optical characteristics and issues in very early development stages and can significantly influence cost reduction (Gomes de Sá and Zachmann 1999), with relatively accurate certainty, which is totally dependable on data input, hardware and software. The output quality may vary deeply on the display's specification and capabilities, such as contrast and colour and the computing engine behind it. In any case, there is an ideal scenario where controlled lighting conditions reflect on an observer's perfect adapted state without reflections, which might be needed as a benchmark (Aydın, Myszkowski and Seidel 2009), but a greater challenge surfaces when real life changing scenarios are intended to be replicated, with a number of different variables, for example, visual maladaptation which is known as the vision acuity and sensitivity decrease when the eye tries to adapt to intense

illumination changes, in other words, the contrast sensitivity and luminance adaptation (Pająk, et al. 2010).

The effects in human vision and adaptation to different light scenarios make the simulation analysis more complex and challenging. At this point it starts to become a dynamic simulation, due to its changing conditions, evolving from a static single scene to a comparison between different condition stages, as will be shown in the PJND plots example of the Optical Simulation, which could be represented in a changing conditions scene.

Since reflections on display decrease legibility, contrast ratio, grey scale and colour reproduction have to be accurately evaluated in worst case scenario situations to mitigate as much as possible the negative light reflection effects, finally setting the display screen luminance properties (Blankenbach, et al. 2014).

From the customer perspective, visualisation and displays are rapidly evolving with larger dashboard displays, in-vehicle AR through head-up displays (HUD), and navigation data, so the complexity of in-vehicle technologies is only increasing. The introduction of self-driving cars will trigger the use of even larger displays, while these should not compromise the driver's visual acuity when the car is being driven. These technological improvements are thoroughly tested before going into market, but there is always room of improvement, and visualisation enables to continue evaluation without the compromise of setting expensive rigs and traditional laboratory trials.

The nature of driving will keep changing with the increase of digital assistants and information systems, aimed to increase passengers' safety and comfort (Bengler, et al. 2014), although displays' size keep growing and the peripheral visual field starts to become an issue, provoking discomfort glare and luminance difference on certain areas, which will become a growing concern fact (Huang and Menozzi 2014).

While in-car displays are improving adopting technologies such as active-matrix organic light-emitting diode (AMOLED) suitable for military and aerospace applications, which changes in display luminance are minimized and reflectance is considerably reduced (Hufnagel, Tchon and Bahadur

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2012), there will be an increasing need of simulating ever changing material characterisation, hardware performance, or light conditions. This is one of the reasons why display positioning has changed from being enclosed in a niche, to a position in plain sight just over the instrument panel.

2.4   Automotive Interior Optical Evaluations

OEM's provide evidence of compliance with specification, but this evidence needs verification to be fully and signed-off by the automotive brand, to corroborate all specifications and functionality work properly with the design and geometry configuration as it is. This standards and regulations must also comply with ISO standards and legislation, which may also vary from one country to another. But there are default studies to be made in order to approve the sign-off of each design and R&D stage.

There is a wide range of analyses and observations that come up through the development stages within the OCAE team at JLR, but for now, the focus will be on the basic evaluations needed to sign off a basic car interior configuration. These optical failure modes refer to: veiling glare, display angle study, instrument cluster study, ghost images in HUD, light traps, switch gear and ambient lighting (JLR Research Report 9926620 02.2 2012).

To establish design all specifications and benchmarks the automotive design should comply with, the evaluations should fall into certain constraints.

For example, in a Veiling Glare (VG) study, there is a Veiling Glare Index (VGI) where anything above 30 VGI is unacceptable, since visual disturbances start appearing on the windshield reflections and may be a hazard for the driver (Research Report JLR 10035762 01 2012). This is the reason why an instrument panel is generally dark, otherwise it would reflect the material's bright colour onto the windshield, causing a veil through the drivers view on the glass.

Another example would be the high-level display front (HLDF) or infotainment screen Performance Study, where the specular reflections caused by the sun in a given position in the sky which could affect the view angle of the driver. For a Jaguar XE screen, set to 400cd/m^2, the optimal

screen angles ranged from 53° to 56° complying with a screen viewing angle of +/- 10° normal to the screen (JLR Research Report 9926620 02.2 2012). This technique is also widely used in digital imaging and video processing (Xiaohui, Weisi and Ping 2007) as well as the aerospace industry. In the latter this method is mostly used to assess instrumentation and display legibility, particularly when sunlight prevents the occupants to see things by virtue of a difference in luminance or chrominance called *"perceived just-noticeable difference"* (PJND) (Sharpe, et al. 2003). In the Jaguar XE case, PJND analysis indicates minimal reflection at 56°, when subjected to 360° rotation and 90° sun elevation. While working with JLR's optical team on these evaluation methods, it started to become evident visualisation outputs could have better resolution and detail, considering the time needed to render the images from the optical test, but that will be further analysed in the next chapters.

2.5   Visualisation Hardware and Software

Computing power is at the core of visualisation performance, whether it is to produce photorealistic digital rendering or video, to real-time raytracing and virtual reality operation. But before getting into cloud processing, high-performance computing (HPC) or 5G technologies, it is important to be aware of some facts within computing capability.

It is important to be aware of Moore's law, which states that transistors in a printed circuit board are doubled every 18 months, hence having twice the performance, which translates in increased efficiency, productivity and economic growth (Liddle 2006). At the same time, software keeps getting better, faster and features richer operations. However, this law or trend is near to its end, due to miniaturization limits in microprocessors' architecture, even considering nanotechnology manufacturing techniques (Markoff 2015), while a new era of computing is being developed ranging from quantum computing to new and more powerful GPU's focused in Deep Learning, which there is already access to.

But with today's tools, in data processing, there is a debate whether the central processing unit (CPU) has less computing power than the graphics processing unit (GPU) and vice versa, and

there are a wide number of variables to consider in this issue. For instance, the memory-transfer overhead adds processing to all applications, and combined with kernel processing, results in more processing time than the GPU processing itself (Gregg and Hazelwood 2011), hence, data transfer becomes a critical issue to take into consideration. The same happens with cloud computing, where in many situations, data transfer exceeds the actual rendering task.

In any case, in order to obtain the most effective performance of the computing power, it is fundamental to identify which tasks are going to be undertaken and assign the most advantageous tool and hardware architecture to each one of them.

What is indisputable is that GPUs being specialised for graphic generation, has a large degree of data parallelisms, which means they can render each pixel on the screen independently and additionally are latency tolerant, while CPUs provide the best single thread performance for throughput computing workloads (Lee, et al. 2010). These facts are important to be recognised, since visualisation performance, especially in real-time rendering will depend on the system's proper configuration and resources designation. As Moore's Law principals start to fade as the end of an era, more sophisticated GPUs start to take special relevance due to their parallelism of data computing, and robust processing, such as Nvidia Volta which is currently one of the technology drivers behind AI and HPC architectures (NVIDIA 2017).

Today, a VR ready graphics card can be purchased as part of a regular computer or separately, without a real need of upgrading the whole system, making it very accessible, in order to run smooth framerates with high quality texturing. This applies to other visualisation and simulation output as well such as a CAVE projection, power wall, or HMD's. However, new devices such as Microsoft HoloLens, has integrated the whole hardware package in a single HMD with outstanding capabilities. To make a point on how a state-of-the-art piece of hardware can integrate such complex systems and tasks into a single product, its components are briefly described in 5 groups (Microsoft 2016):

1) Processors, memory and power

- Intel system on chip (SoC) 32-bit processor which can be found on cell phones running windows 10. Holographic processing unit (HPU) which functions as the graphics card. 64GB Flash, 2GB RAM. 2-3 hours of active use, 2 weeks standby, fully functional when charging.

2) Sensors

- Inertial measurement unit (IMU) to track the user's movement. 4 environment understanding cameras. 1 depth camera. 1 HD video and 2MP camera. 4 microphones. 1 ambient light sensor. Mixed reality capture.

3) Optics

- 2 HD 16:9 light engines. Automatic pupillary distance calibration. See-through holographic lenses (waveguides).

4) Input/ Output/ Connectivity

- Built-in speakers. Audio 3.5mm jack. Wi-Fi 802.11ac. Micro usb2.0. Bluetooth 4.1 LE.

5) Human Understanding

- Spatial sound. Gaze tracking. Gesture input. Voice control.

While the applications are still in development by using Unity and Visual Studio, it becomes evident the wide range of visualisation possibilities it entails, and the potential number of NPD applications which can be generated from a HMD, engineered with an outstanding straight-forward usability, in contrast with the traditional VR kit, where an OLED screen is used in a closed visor, with hand-held devices detected by a couple of cameras for movement tracking positioned on each corner of a given squared area, plus the computing power. It is true that VR and AR differ in nature and applications, but the visualisation outputs equally suggest more immersive and explicit environments.

These technologies are exposed in order to set a perspective of the visualisation capabilities and what sensory experiences are being targeted by technology, as part of an immersive experience.

2.5.1 Augmented and Virtual Reality

AR and VR technologies are getting its way predominantly through HMD's. VR has been around since the early 1960's (Schina, Lombardo and Corallo 2016), but has only recently found the proper moment in the massive market. From cell phone devices to more elaborate hardware kit such as the HTC, VR is positioning as one of the technological trends that will set the pace in the coming years, from entertainment and broadcasting to surgery and judicial trials, where objects are presented positioning the spectator in a recreated virtual scenario, communicating in a more realistic and immersive way.

On the other hand, AR offers an interaction between a real scenario and digital content, sometimes called mixed reality. Two of the main companies leading the industry are Microsoft HoloLens and Meta-Vision, which by the end of 2016, are still in development phase, but with a huge investment to produce results in the next years. The current AR / VR industry leaders are shown in *figure 2*.

Figure 2. AR/VR leaders. (Digi-Capital, Augmented / Virtual Reality Report Q2 2016. 2016)

In the manufacturing industries, VR and AR will allow to produce more effective design processes to improve quality, cost and time, supporting representation of objects, processes activities and principles (Marinov 2001), taking the place of regular screens or monitors, to give way to immersive and more interactive environments, where instead of having a 2D feedback, many people interact in a single scene.

These people can come from many different teams, with access to a determined virtual project, where their input is needed such as: product lifecycle management (PLM) integration in Virtual Prototyping, Immersive Virtual Testing through simulation, Virtual Training executed by human resources, through the virtual scenario, Collaborative Virtual Review for design, engineering

and management and even a Virtual Manufacturing Process review and factory layout (Schina, Lombardo and Corallo 2016), where many processes can be optimised.

Currently AR applications are being developed for pass-through HMD's, where the digital content is projected through the HMD's lens, allowing the user to interact with the real environment, but in the past smart phones have been the most popular tool, by using the phone's screen to display digital content in the current camera's image, like Hyundai owner's manual. However, in the next years HMD's will be the interface used for mixed reality as the most common tool, and even as a support of the regular computer screen, which could be completely replaced in the future for certain tasks.

2.5.2   Artificial Intelligence

This tool is emerging as a dominant resource due to its computing power and the massive amounts of data it can process. Graphics cards are being used in a variety of industries from big data to simulation (Taddy 2018). For visualisation, the processing capability, speed and quality is giving giant leaps at this very moment, but first, a distinction that should be made between Artificial Intelligence (AI), Machine Learning (ML) and Deep Learning (DL). AI is the broader concept where a machine executes operations on a set of stipulated rules or algorithms and encapsulates the other processes such as ML and DL. ML is a technique for the machine to make predictions based on provided data. After the algorithm tries x number combinations within the data, it is able to learn by the differing characteristics (Kurzweil 2007).

Deep Learning works through artificial neural networks based on short long-term memory, which makes possible to detect sequences, like speech recognition for example (Sak, Senior and Beaufays 2014). This same neural network architecture is used to perform other advanced tasks with large amounts of data and computation, necessary to build up the machine database and enable the AI to perform "intelligent" operations. Summed to this, AI will allow software to learn from data & experience and will be capable to rewrite itself with huge amounts of parameters and information to

then apply and correlate applications such as computing graphics, scientific computing, deep learning and data science. In other words, deep learning and neural networks is just an algorithm that aims to mimic the way a human brain makes decisions (Buchanan 2007).

AI will have a profound impact in the way things are done in industry, from computing digital such as design and engineering, to marketing and even consumer trends. At this point, it becomes critical to consider how Technology Management will impact the outcomes of R&D, and apply PLCM processes, since constant optimisation will become a day to day factor with the necessity of updating and correlating everything surrounding this application. Today, companies such as "Mapd" make possible to reengineer and refactor entire databases in order to link and analyse dependencies, relationships and even graphic outputs (Mapd 2017).

Further on, in visualisation, there are constant improvements in hardware and software. For instance, in VRED 2019.3 Professional package, which was released in January 2019, it was featured for the first time the option of using CPU raytracing with GPU denoising using deep learning to predict raytracing and improve time and quality in the process. This is an important fact, since Moore's Law may be starting to shift, and its predictions may be already happening.

2.6 Visualisation & Simulation in New Product Development, Product Lifecycle Management and Decision Making

The early development stages of product creation are critical in shaping the product's performance, overall cost and technological input. Visualising simulations is becoming one of the most effective decision-making tools in terms of communicating and assess designs that are not already available physically. AR and VR, with a staggering investment of $2 billion by the second trimester of 2016 (Digi-Capital, Augmented / Virtual Reality Report Q2 2016. 2016), states with absolute certainty that these immersive technologies are here to stay and develop long way further.

The early adoption of new technologies such as these, can represent a big leap forward in innovation, setting new industry standards. The integration of new technologies is directly related to PLM, since it is shaped according to Computer-Aided Design (CAD), Engineering Data Management (EDM), Product Data Management (PDM) and Computer Aided Manufacturing (CAM); at the same time, it is strongly related to Systems Engineering as a major methodological component (Grieves 2011).

Coordination between these numerous processes, tools and individuals active in the NPD process represent the first challenge of the product's plan, collaboration being one of the first bottlenecks to tackle (Sadeghi, Masclet and Noël 2012), and which will be continuously present throughout the development phase. Negotiations, design reviews and all major decision making concerning the product are done through careful information management and data exchange, but sometimes information technology limits flexibility establishing standardisation constraints (Merimod and Rowe 2012) , and that's the point where an adequate PLM software becomes very important in terms of information exchange.

As part of the PDM, visualisation postulates itself as a very efficient tool, where product reviews can be done more efficiently and, in less time, while trying to access any specific design iteration. Moreover, the collaboration between different stakeholders may be more dynamic and clearer, using for instance multiple HMDs, while assessing a specific design review between various development teams in different parts of the world, where different knowledge exchange obstacles emerge such as organisational, geographical or language obstacles increase the failure possibilities (Bjorn and Ngwenyama 2009).

PLM and PDM has greatly improved the manufacturing industry giving access to documents and 3d models which reinforce the share of the lifecycle information (Song, Bo Hu and Chai 2007), but the expansion of content management is in continuous evolution and new ways of communication such AR and VR environments are the next natural step in data management and collaboration. In previous literature, it has already been proven that pictures sent through the PLM

network, with basic explanations are more effective than detailed written technical descriptions in some cases, in some others, object 3D visualisations reduced issue slippages without the intervention of external help (Merimod and Rowe 2012).

One important characteristic within the Enterprise Resource Planning (ERP) among many others, is that it was designed to avoid the silo effect caused by the legacy systems, interconnecting different departments by placing the proper gatekeepers that make the right data accessible to the different stakeholders, at the right time, depending on the project necessities. In this regard collaboration is fostered with a very flexible scheme which can adapt to change. Visualisation and simulation can endorse this kind of systems by making information readily available in a more comprehensible way, especially in design review and knowledge transfer stages, and by expanding the system's technology capability, the time/cost/quality issues can be significantly improved from both SE which deals with product realization and specific tasks (Grieves 2011) and PLM perspectives. On the other hand, it can provide feedback when there is a lack of experienced-based knowledge, which is not available to everyone and reduces the project performance (Sivri and Krallmann 2014).

By this, an assumption can be made regarding the addition of digital media data sets, where virtual and augmented reality scenarios can be added to the product description and specification, up to the point where the viewer can access walkthroughs with information provided by the previous people involved in a determined part or finished product, with accurate recommendations and issues, for example the Systemic Optical Failure modes, where previous standards had been used and areas of improvement can still be made, presented in an immersive and more explanatory experience.

2.7 Optical Principles Lighting, Photometry, and C.I.E.

In 1913 the Commission Internationale de l'Eclairage C.I.E. (International Commission on Illumination) was founded with the objective of developing standards and procedures of metrology in the fields of light and lighting (Commission Internationale de l'Eclairage 2016), and since then it became one of the most respected organisations in charge of light, illumination and colour spaces regulation.

By 1931-32, CIE defined the Standard Observer for Colorimetry and the 1931 CIE System of Colorimetry, which principles are still being used as the foundation of many evaluation systems regarding colorimetry and illumination (Schanda 2007). By defining wavelengths in the visible spectrum of the human eye, CIE 1931 RGB Colour Space and Cie 1931 XYZ Colour Space (C.I.E. 1931-1932) set the foundation of today's light and colorimetry standards, and for the last 85 years, CIE has published a number of improvements and studies which are still today's standards of measurements for vision and colour, light and radiation, interior environment and lighting design, lighting and signalling for transport, exterior lighting, photobiology and photochemistry and image technology.

This light or visible wavelengths for the human eye, reside in the region of the electromagnetic spectrum between 380 and 780 nanometres (nm) (Rea 2013). The rest of the electromagnetic spectrum can be measured through radiometry. In other words, the boundaries of this spectrum are the ultraviolet and infrared light, and in between all the visible colours are perceived, depending on its wavelength (*figure 3).
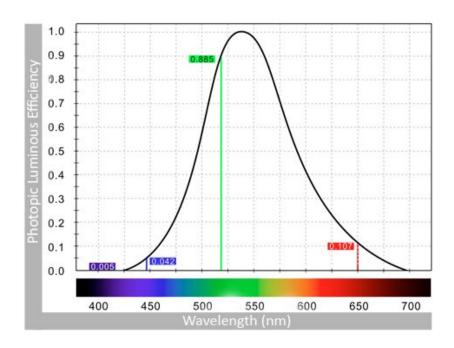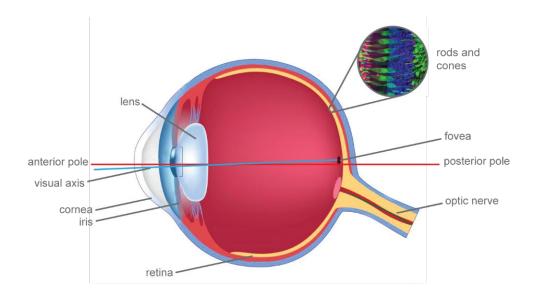
The way electromagnetic radiation moves in space is not yet entirely known, but light is normally produced by a glowing body in a process called incandescence (Kuehni 2005). The behaviour of light and how we perceive has many characteristics depending on the different variables involved, thus there are some terms to get familiar with before getting into greater detail. Photometry is the way we measure light and as previously mentioned, the methodology has been around for almost a hundred years.

In the human eye, rods and cones translate this photonic energy into electrochemical energy and is communicated through the optical nerve to the brain (Kuehni 2005). The Photopic Luminous Efficiency Function $V(\lambda)$, shows the spectral sensitivity of the cone photoreceptors in the fovea (-2deg) (*figure 4*) and is the only function used in commercially available in photometric instruments. There are other functions with using different light conditions: $V'(\lambda)$ scotopic or dim light conditions, $V_M(\lambda)$ a second photopic luminous efficiency function and $V_{10}(\lambda)$ with a photopic 10-deg spectral sensitivity (Schanda 2007).

Human eye section

Figure 4. Human eye section. (Kuehni 2005)

The base unit is called ***candela*** (cd), which is a measure of the luminous intensity of a light source in a particular direction and produces intensity differences throughout. (Rea 2013). Its radiant intensity is of 1/683 watts (W) per unit solid angle at 555nm, unit also known as ***lumen*** (lm)*; the spectral power distribution (SPD) of the radiation emitted by a source is integrated with V(λ) to establish the photopic luminous intensity in candelas of the source in the direction of measurement and finally this quantity is equal to the number of lumens per steradian (sr) in the direction being measured (lm/sr) (Schanda 2007).

With these units as the foundation of the system there can be determined other ratios of light, such *as luminance* which is known as photometric brightness and is basically the measure of intensity of light per unit area in the direction of view and is measured in units of nits or cd/m^2. 1 candela equals 1 lumen per steradian or cd = lm/sr. Thus, an isotropically emitting light source with luminous intensity of 1 cd has a luminous flux of 4π lm = 12.57 lm (Schubert 2006). These equivalences will become handy to correlate values when measurements are taken from the simulation and physical measurements.

Illuminance or lumens per surface area, is the luminous flux incident per unit area and is measured in *lux=lm/m²*. In *Table 1* these photometric units are summarised and compared with radiometric units.

Photometric	Unit	Equivalence	Radiometric	Unit
Luminous intensity (I)	Candela (cd)	lm/sr	Radiant intensity (I_e)	Watt per steredian (W/sr)
Luminous flux (F)	Lumen (lm)	lm/4πsr	Radiant flux (φ) (optical power)	W
Luminance (L)	Nit (lm/m²)	cd/m²	Radiance (L_e)	(W/sr m²)
Illuminance (E) (intensity of illumination)	Lux (lx)	lm/m²	Irradiance (E_e) (power density)	(W/m²sr)
Luminous efficacy	-	lm/W		

Table 1. Photometric and Radiometric equivalence based on (Arecchi, Messadi and Koshel 2007) (Schubert 2006)

Other units such as *lumens per watt* (luminous efficacy) is equal to the eye sensitivity function V(λ) multiplied by 683 lm/W. V(λ) is relevant only to cones, from which there are 3 different types: long (L cones), middle (M cones) and short (S cones), depending on the wavelength peak sensitivity they have and at the same time each of these 3 types provide the trichromatic colour vision in which colorimetry is based, although S cones do not come into play in the photopic (*figure 5)* luminous efficiency function (Schubert 2006).
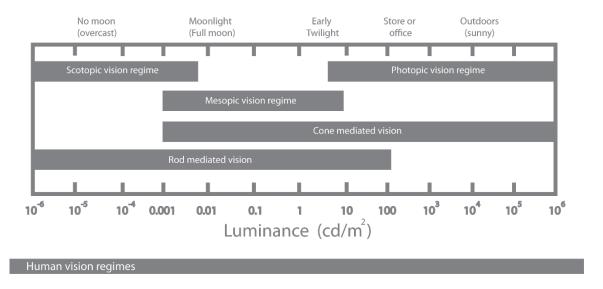
Figure 5. Human vision regimes. (Arecchi, Messadi and Koshel 2007)

At the same time, depending on the nature of the material, light can react and interact with it in many ways such as *absorption, reflection, scattering and transmission*, *refraction*, *interference* or *diffraction*. Each of these conditions will be reviewed closely further on, as the research unfolds. It is also important to mention that the *intensity* concept entails another definition called *solid angle* (ω), which is a 3d angular volume formed by the surface area of a sphere *(figure 6)*. The steradian is the unit of this angle, with 4π steradians in a complete sphere (Arecchi, Messadi and Koshel 2007).
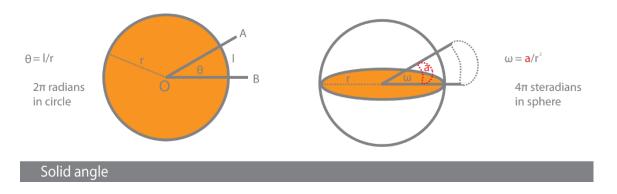
Figure 6. Solid Angle diagram. Based on (Arecchi, Messadi and Koshel 2007)

2.7.1   Colorimetry

"Colour matching is the basis for colorimetry", although *colour appearance* is another approach used, but for its subjective appreciation it is imprecise. By colour matching the optical

radiation emitted from a light source or even an object reflecting this light source, can be described with mathematical precision (Schanda 2007). Nevertheless, *colour appearance* terms can be used to describe and communicate fundamental colour characteristics. *Hue, lightness and chroma* are the 3 features to consider. *Hue* is the different colour gamut in the spectre which runs from red to violet. *Lightness* is usually referred as brightness. Finally, *chroma* is how saturated the colour appears in its own intensity, for example, is the different violet tones with the same lightness *(figure 7).*

Colour appearance dimensions
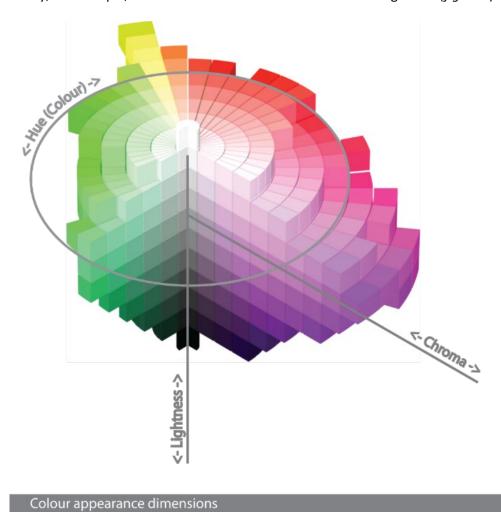
Figure 7. Colour appearance dimensions. Based on (Schanda 2007)

C*olour* matching, which is the method we are ultimately interested in, is the method used throughout the industry to describe the optical radiation from a source or body reflecting it, by measuring the spectral power distribution of the source or the spectral reflectance of the object. It uses three main colours which can be used to match any light source with mathematical precision,

even in different contexts. These primary lights are regularly narrowband, and seen by themselves appear in red, green and blue (Schanda 2007). For this reason, any two colours may look the same, but they may have a different spectral signature, in other words, different red, green and blue (RGB) combination. This is called *metamerism,* and it can represent technical problems industry when it comes to colour matching, since a hue may change depending on the light source, producing colour inconsistencies between two different materials with apparently the same colour (Kuehni 2005).

The CIE 1931 system of colorimetry *(figure 8)* is based on these 3 primary colours, each with its own matching function x(λ), y(λ), z(λ), conforming the *tristimulus values* (Schubert 2006), and the chromaticity coordinates are calculated from these as:

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z}$$

The value of *Z* is calculated analogously:

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

It is important to point out that *z* chromaticity can be taken from *x* and *y*, being that the reason of using the *(x, y)* chromaticity diagram, where red and green have the large values for *x* and *y* and blue has the *z* values (Schubert 2006).
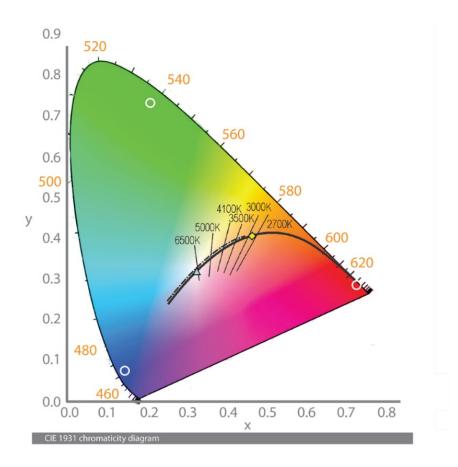
Figure 8. CIE 1931Chromaticity diagram. (C.I.E. 1931-1932)

Chromaticity and colour may be used as synonyms only when the brightness level of the light source does not variate. According to C.I.E. (1986) colour is much more than just the coordinates in the chromaticity diagram, since brightness or luminous intensity may also change the light source hue (Schubert 2006).

It is important to mention other parameters such as *colour rendering index* (CRI) and *correlated colour temperature* (CCT). The first one is important because it is a popular tool used in industry and measures the amount of chromaticity shift between eight to fourteen samples of spectral reflectance illuminated by a fabricated light source and is compared to a reference or ideal natural light of the same colour temperature (Schanda 2007). It is directly related with the *correlated colour* temperature (CCT) which the colour variation of the light source, depending on the incandescence temperature, going from yellow to blueish tones, which are translated as warm or cool sources of light, based on the Kelvin scale, where over 5000 K, cool colours are assigned and

from 2700 to 3000 K is the warm colours region. (*figure 8).* The reference source such as a blackbody

radiation or incandescent light has a CRI of 100, while zero would be the lowest (Schanda 2007).

2.7.2   Light & Materials Interaction

Principles of light and colour are essential in automotive optical design and simulation, but it is

useless if we cannot relate it to our environment. The response of materials to an illumination

source is of the utmost importance in optical analysis. There are 3 important features in the way

light behaves *(figure 9)*, depending on the material properties: *transmittance* (τ)*, reflectance* (ρ) *and*

absorptance (α) (Arecchi, Messadi and Koshel 2007)**.**
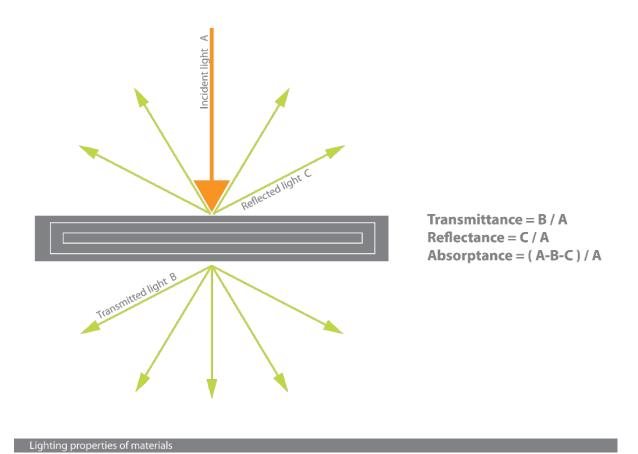
Figure 9. Lighting properties of materials. Based on (Arecchi, Messadi and Koshel 2007)

Transmittance as its name states, is the materials' ability to transmit radiant energy, while

the internal transmittance is related to energy loss by absorption, there are different transmittance

types such as hemispherical, spectral and directional transmittance depending whether it is radiant, spectral or spectral radiant fluxes what is being measured (ISO9288:1989 1989). *Transmittance* and *reflectance* can also be converted to a log scale and it is called *optical density* (OD), which is based on magnitude sequence, rather than a common linear scale (Arecchi, Messadi and Koshel 2007).

These transmittance measurements equally apply to reflectance, where there are 3 main kinds depending on the material's surface: *Lambertian or diffuse, specular or mirror-like and haze reflection.* In a *Lambertian surface*, incident light is reflected in many different directions and scattered above the reflective surface with the same radiance distribution in all directions, making it impossible to determine where the incident light comes from. Some examples of a Lambertian surface would be plain white paper or glass with sandblast finish (Arecchi, Messadi and Koshel 2007). There is no such a thing of a perfect Lambertian surface, but to determine a *reflectance factor* (R), a supposedly *perfect reflecting diffuser* (PRD) is considered to obtain the reflected light ratio from a regular reflecting material to the quantity of light that would result from a PRD equally illuminated.

Thus, the *reflectance factor* is related to the *bidirectional reflectance distribution function* (BRDF), which is the radiance of a surface divided by its irradiance (Arecchi, Messadi and Koshel 2007).

The *specular reflection* occurs with a perfectly smooth surface such as a mirror, which reflects light in exactly the same angle as the incident light. *Haze reflection* is somehow in the middle of the specular and Lambertian ones. The light reflected is scattered in many directions, but the higher quantities of light still follow the specular reflecting angle *(figure 10)*.

Lambertian

Specular

Haze

Light Reflectance
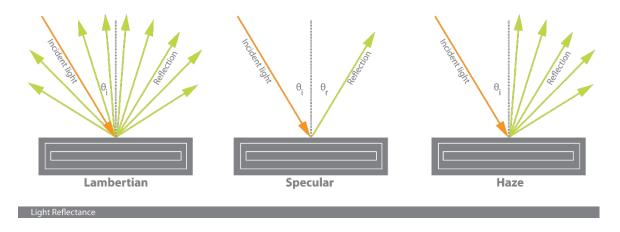
Figure 10. Light reflectance. Based on (Arecchi, Messadi and Koshel 2007)
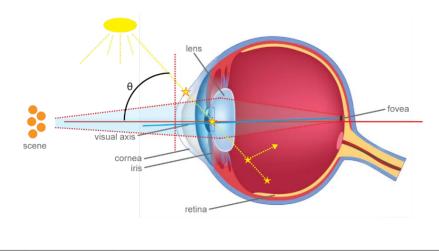
2.7.3 Contrast

While driving, road lights, signs and other cars visibility represent a major concern, and in this context, contrast can be understood as the luminance difference between an object and its background. For good road visibility, there are many elements that come into play such as illuminance on the road, how it is perceived by the driver and small targets visibility (Boyce 2014). In an automotive design environment this characteristic is of the utmost importance, since the correct dashboard instrument legibility and displays should always be optimal in combination with the ambient conditions. Low contrast makes elements become more difficult to distinguish between them, resulting in a mayor optical effort that affects the reading rate (Legge, Rubin and Luebker 1987).

2.7.4 Glare

In general, glare occurs when there is an inappropriate luminance disposition or an unfit range of luminance values, causing vision to experience discomfort or reduce the ability to see details and objects (017/E 2011). Within the glare concept there are two main types: *discomfort glare,* which is just distracting and inconvenient, and *disability glare* which is the loss of visual performance caused

30

by the scattering light of a glare source going through the eye lens and fovea (*figure 11)*, taking a bright veil effect (van Bommel 2015).

Figure 11. Glare light spread in human eye. Based on (van Bommel 2015)

2.7.5 Veiling Glare

There are a number of definitions for the phenomena depending on the context. It is found from lenses to digital displays, and in general it could be defined as incident light which causes reflections and "ghost" images between 2 or more surfaces (Imatest 2016). In this case, veiling glare will be referred to as reflected light from the dashboard towards the windshield, which generates loss of clear view of the road, due to the visual fogging projected on the windscreen, loss of shadow detail, contrast and colour (*Figure 12).*

Veiling Glare Diagram
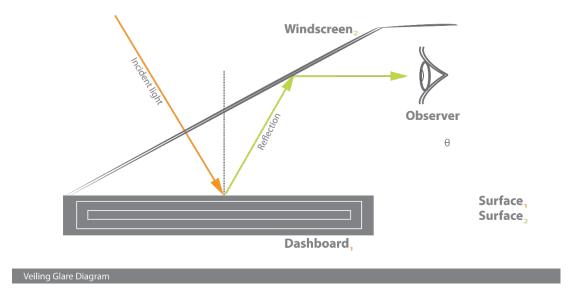
Figure 12. Veiling Glare Diagram. Based on (Boulos, et al. 1997)

This diffuse and specular scattering of light through the windscreen's surface intensifies when the windscreen rake angle increases, causing less visual acuity performance, with a 70-degree limit (Schumann, et al. 1997). Additionally, textures have great impact on the amount of reflected light on windscreen, in particular at large angles of incidence (Boulos, et al. 1997). There are even studies which suggest the use of antireflection-coated lenses for night-time driving, linked to the correct windscreen rake angle to get the most optimal light transmittance (Walsh 2009).

A number of patents have been submitted dealing with this kind of effect, including veiling glare control in a holographic windshield (Smith 1994) or Actively Controlled Texturing Systems (Keefe, et al. 2015), which by producing surface wrinkles using active material actuation, can produce changes in how surfaces interact with light. These advances represent a step forward in technology implementation as a manufacturer, and the next generation of design solutions adding up to the automotive attributes. Other solutions such as polarization layers developed by PPG industries (Munro 2013) used on the dashboard surface, help to reduce light reflection unto the windshield.

Other basic considerations reside on legislation and standards, such as ISO 3538 which deals with "Road vehicles. Safety glazing materials. Test methods for optical properties" (I. O. ISO 1997), and ISO 9358 which addresses "Optics and optical instruments". Veiling glare of image forming

systems, definitions and methods of measurement." (I. S. ISO 1994). The latter has to do with imaging

systems which might be of special interest when choosing original equipment manufacturer (OEM)

parts such as on-board cameras for a specific design configuration, but still should be considered as

part of the visualisation parameters and design scheme.

2.8   Defining Realism and Measuring Perceptual Quality

According to James Ferwerda, (Ferwerda 2003) there are 3 types of realism in computer graphics:

1.   Physical realism, where the image provides visual stimulation

2.   Photo-realism, where the image provides visual response

3.   Functional realism, where the image provides visual information

This study will aim to achieve the later for design and engineering purposes, where functionality

is pursued for achieving a product development optimisation and possible High-Fidelity graphics

(Ferwerda 2003).

On the other hand, measuring perception is qualitative in nature, so by relying on typical image

attributes such as brightness, contrast, reproduction of colours and details, (Cadik, et al. 2007) it is

possible to quantify how an image is perceived depending on the combination of these attributes.

Moreover, in today's rendering technologies, there is a large array of tone mapping methods

which can send different visual stimuli perceptions. The search for the appropriate overall image

quality (Cadik, et al. 2007) will be determined throughout the development of the visualisation

outputs.

3   Visual Simulation Prioritisation

To establish the research problem definition, the first approach is to review the issues faced by the optical and visualisation teams within JLR, and the potential stakeholders reliant on visualisation within the business. By collecting data such as workflow resources or task timing, the goal is to establish an optimisation frame, aiming to identify challenges and propose the way improvements can be executed.

3.1   Visualisation Context

A basic visualisation roadmap has been devised to locate different stages of the failure mode differentiation and the critical aspects linked to it within the product development process. These aspects are associated between them in many levels, from the product development process to the final product performance.

In the automotive industry there are various Optical Failure Modes (OFM) that are currently addressed through lighting simulation analysis. As a preliminary outline, the related fields and resources involved in lighting simulations visualisation are classified in different clusters *(figure 13)*, placing visualisation at the centre of it. The purpose of mapping the visualisation context, is to portray the variables that affect the simulation and visualisation performance, considering business needs, hardware and software, and product requirements to be able to establish a hypothesis of the factors directly or indirectly affecting it.

After going through several depictions of the relation between these clusters, the Failure Mode Detection and Analysis surged as the primal argument to explore at first, being the foundation of accurate visualisation.

Figure 13. Visualising Lighting Simulations Context

3.1.1 Systemic Optical Failure (SOF) Modes

There are design aspects which can be significantly improved in alignment with the continuous quality improvement strategy from the beginning of a new project, with the appropriate use of tools and information traceability. As in a regular Failure Mode and Effect Analysis (FMEA), the purpose of these kind of evaluations is to make sure any particular design configuration performs as it was planned and also to know in which conditions a malfunction can be triggered.

As a fundamental objective, an alternative methodology within the Product Creation Delivery System (PCDS) must be implemented, in order to anticipate and improve any possible design issues within the existing product performance, user experience and achieve a zero-defect NPD strategy. In the current PCDS scheme, there are 4 general stages of the product development process: strategy, delivery, launch and production. Design Optical Quality (DOQ) is implemented in the first two stages of the overall process and should deliver the best possible interior and exterior optical design solution (*figure 14*).
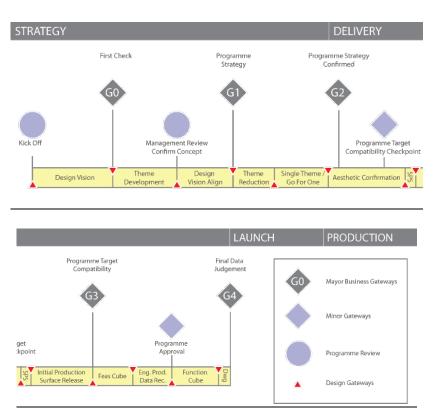
Figure 14. Jaguar Land Rover PCDS

Occasionally there is a demand of immediate action to certain evaluations, but when the line between different issues is not very clear concerning urgency or business objectives, different prioritisation tools have to be used to determine which projects are the most appropriate and suitable according to the product development and foresight plans.

As a first approach, 3 brainstorming sessions were set up at JLR Gaydon, as a general overview of the optical product themes. The results were then correlated to the running optical issues, and as a result 4 general groups emerged, as a more serious optical issues selection.

The "Current SOF Modes" column (*table 2),* shows which optical failure modes have been tested throughout previous and present projects. These modes cover the analysis of an optimal performance towards the user experience, and from this point more specific and detailed SOF modes are derived.

The rest of the categories (Current Missed to Capture SOF modes, Future Expected Technologies – Optics/Light Involved and Dream Technology Predicted Failure Modes) were determined bearing in mind the customer needs, prospected technologies and trends, and integrating it to selection sessions, open among JLR engineers from different departments.

Through these sessions 3 main groups of subjects participated to classify each research topic: Human-Machine Interphase (HMI), Cabin Systems (CS), External Lighting (EL), and from this 4 basic groups different topics were obtained:

1. Visual distraction - HMI

2. Veiling Glare – HMI, CS

3. HUD variation analysis – HMI, CS

4. Head-up displays (HUD) - HMI

5. Colour harmony between ambient lighting and switchgear – CS

6. Intensity harmony between ambient lighting and switchgear

7. Digital simulation in dashboard and interiors – HMI, CS

8. Side rear view mirror opacity (dimmer)

9. PJNDs plots are clear, but we still see sunspots on displays

10. Accuracy on colour change icons in sun light

11. Optical effects of dirt/dust/fingerprints

12. Visual activity

13. Optical design in exterior lighting - EL

14. Levels of visual accuracy in external environment – EL, CS

15. Simulation of reflections and lit commands

16. Modular mood lighting

17. Lit on-board equipment and visibility validation

18. Display and interphase lit simulation

19. Mismatch on lighting

20. Performance in relation to environmental conditions

21. Display legibility

22. Resolution and size of camera output image

23. Night-time assessment vs. day-time specs

24. FUTURE

25. DREAM

Current Missed to Capture SOF modes were identified as the next set of projects which have not been measured and were recognised as a valuable set of data to complement to a greater extent of detail the existing failure modes while increasing the added value in the current product development process.

SOF modes			
Current SOF modes	Current Missed to Capture SOF modes	Future Expected Technologies – Optics/Light Involved	Dream Technology Predicted Failure Modes
1 Veiling Glare 2 Display legibility 3 Visual activity 4 Mismatch on lighting performance in relation to environmental conditions 5 Resolution and size of camera output image 6 Night time assessment to day time specs	(INT) Colour harmony between ambient lighting and switchgear (INT) Intensity harmony between ambient lighting and switchgear (EXT) Side rear view mirror opacity (dimmer) (INT) PJNDs plots are clear, but we still see sunspots on displays (EXT) Accuracy on colour change icons in sun light (EXT) Optical effects of dirt/dust/fingerprints	(EXT) Cross cabin displays - Gesture control features - Autonomous features (EXT) Light into camera lenses (EXT) Larger screens increase cabin lights at night (EXT) New heap technology reflecting into mirrors/cameras	Mirror replacement for displays Screen on steering going to create driver distraction Hybrid augmented/physical simulations (Hololens+volume rig "dashboard")

Table 2. Optical Failure Modes

In order to identify the complete spectrum of optical design issues there is a need to correlate past, ongoing and prospected projects within the PCDS. Define, Measure, Analyse, Improve, Control (DMAIC) became the first consideration as the foundation of the SOF mode analysis, which will correlate with JLR's PCDS to be integrated into the development scheme, focusing upon workflow and value stream, since the resources used along the process through lighting simulations and visualisation will provide the final process improvement and added value. This is also a tool used in Lean Sigma to improve or stabilise processes or a specific operative problem, providing valuable data for a complete value stream mapping (Tyagi, Choudhary and Yang 2014).

Within the Define stage, there are a number of steps to establish which project ideas are worth looking into, considering different voices that influence a project formulation: voice of the market, voice of the process, voice of the business and voice of the associates (Ortiz 2008).

The starting point considered the preliminary SOF modes selected by JLR's Optical Computer Assisted Engineering (OCAE) team. As a first step, the Current Missed to Capture SOF Modes have to be prioritised by comparing a list of criteria to its relative importance and impact in the product output, determining which one of them has the strongest, added value and entails a greater amount of attention resolving critical trade-offs in the product planning and design.

3.1.2   Project Prioritisation

There are two kind of prioritisation matrices that will be useful for the SOF selection. The first one *(table 3)* gives an outline of which project weighs more against one another by pointing out which topic has more relevance for the business and is useful to obtain a quick assessment of the projects' attributes in relation with objectives, as shown in *(table 3)*.

	Colour Harmony between AL & SW	Intensity Harmony between AL & SW	Side rearview mirror opacity	Sun spots on Displays (PJNDs clear)	Accuracy on Colour Change Icons in S...	Optical effects of dirt, dust, fingerprints	Attribute Criteria Weight	Percent of Total Criteria
Colour Harmony between AL & SW		1.0	0.1	0.1	0.2	10.0	8.00	18.2%
Intensity Harmony between AL & SW	1.0		0.1	0.1	0.2	10.0	9.00	20.5%
Side rearview mirror opacity	10.0	10.0		0.1	5.0	10.0	7.00	15.9%
Sun spots on Displays (PJNDs clear)	10.0	10.0	10.0		10.0	10.0	10.00	22.7%
Accuracy on Colour Change Icons in	5.0	5.0	0.2	0.1		5.0	6.00	13.6%
Optical effects of dirt, dust, fingerprint	0.1	0.1	0.1	0.1	0.2		4.00	9.1%

100.0%

10	Attribute in yellow column is extremely more important than the attribute in gray column
5	Attribute in yellow column is slightly more important than the attribute in gray column
1	Attributes are equal in importance
0.2	Attribute in yellow column is slightly less important than the attribute in gray column
0.1	Attribute in yellow column is extremely less important than the attribute in gray column

Table 3. Criteria weight trade study

As the previous table shows, the topics compared between them and assigns a criteria weight. This is a useful decision-making tool, which gives a value to each topic's priority in terms of impact, urgency and complexity. In the figure below, Side Rear View Mirror Opacity appears to be one of the most pressing problems to solve at that moment in time, against the other topics. But there is yet another type of criteria which should be considered.
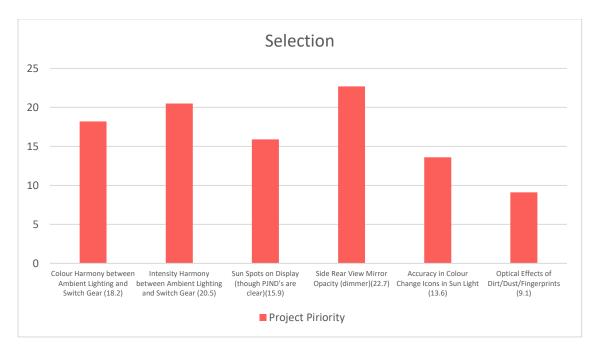
Figure 15. Criteria weight graph from table 3.

The second is the operative criteria review, where every attribute contributes with a ratio to the whole matrix, and in consequence much more accurate information is retrieved. First operative critical criteria are determined, such as ease of hardware change, reliability, etc.

Criteria Weight	1	2	3	4	5	6	7	8	9	Total	Decimal Value
1 Ease of Hardware Change	■	10	.1	.2	5	10	5			30.30	0.20
2 Dimensions and Config Change	.1	■	0.2	1	0.2	0.1	0.2			1.80	0.01
3 Reliability	10	5	■	1	1	.2	10			27.20	0.18
4 Redesign Complexity	5	1	1	■	.1	.1	5			12.20	0.08
5 Technical Risk	.2	5	1	10	■	.1	.1			16.40	0.11
6 New Development Cost	.1	10	5	10	10	■	10			45.10	0.30
7 Lead Time	.2	5	.1	.2	10	.1	■			15.60	0.10
8 Criterion #8								■		0.00	0.00
9 Criterion #9									■	0.00	0.00
Column Totals	15.60	36.00	7.40	22.40	26.30	10.60	30.30	0.00	0.00	148.80	1.00

Table 4. Projects' criteria comparison matrix

Ease of hardware change

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	0.20	0.20	0.20	5.00				6.60	0.08
2 Intensity Harmony between	1.00	X	0.20	0.20	0.20	5.00				6.60	0.08
3 Sun Spots on Display (thoug	5.00	5.00	X	5.00	5.00	10.00				30.00	0.38
4 Side Rear View Mirror Opaci	5.00	5.00	0.20	X	5.00	5.00				20.20	0.25
5 Accuracy in Color Change Ic	5.00	5.00	0.20	0.20	X	5.00				15.40	0.19
6 Optical Effects of Dirt/Dust/F	0.20	0.20	0.10	0.20	0.20	X				0.90	0.01
7							X			0.00	0.00
8								X		0.00	0.00
9									X	0.00	0.00
COLUMN TOTALS	16.20	16.20	0.90	5.80	10.60	30.00	0.00	0.00	0.00	79.70	1.00

Dimensions and Config. C

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	0.20	0.20	0.20	1.00				2.60	0.04
2 Intensity Harmony between	1.00	X	0.20	0.20	0.20	1.00				2.60	0.04
3 Sun Spots on Display (thoug	5.00	5.00	X	5.00	5.00	0.10				20.10	0.29
4 Side Rear View Mirror Opaci	5.00	5.00	0.20	X	5.00	1.00				16.20	0.23
5 Accuracy in Color Change Ic	5.00	5.00	0.20	0.20	X	5.00				15.40	0.22
6 Optical Effects of Dirt/Dust/F	1.00	1.00	10.00	1.00	0.20	X				13.20	0.19
7 0							X			0.00	0.00
8 0								X		0.00	0.00
9 0									X	0.00	0.00
COLUMN TOTALS	17.00	17.00	10.80	6.60	10.60	8.10	0.00	0.00	0.00	70.10	1.00

Reliability

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	0.10	0.10	0.10	5.00				6.30	0.05
2 Intensity Harmony between	1.00	X	0.10	0.10	0.10	5.00				6.30	0.05
3 Sun Spots on Display (thoug	10.00	10.00	X	5.00	5.00	10.00				40.00	0.34
4 Side Rear View Mirror Opaci	10.00	10.00	0.20	X	5.00	10.00				35.20	0.30
5 Accuracy in Color Change Ic	10.00	10.00	0.20	0.20	X	10.00				30.40	0.26
6 Optical Effects of Dirt/Dust/F	0.20	0.20	0.10	0.10	0.10	X				0.70	0.01
7 0							X			0.00	0.00
8 0								X		0.00	0.00
9 0									X	0.00	0.00
COLUMN TOTALS	31.20	31.20	0.70	5.50	10.30	40.00	0.00	0.00	0.00	118.90	1.00

Redisign complexity

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	5.00	5.00	5.00	5.00				21.00	0.26
2 Intensity Harmony between	1.00	X	5.00	5.00	5.00	5.00				21.00	0.26
3 Sun Spots on Display (thoug	0.20	0.20	X	0.20	5.00	10.00				15.60	0.19
4 Side Rear View Mirror Opaci	0.20	0.20	5.00	X	1.00	5.00				11.40	0.14
5 Accuracy in Color Change Ic	0.20	0.20	0.20	1.00	X	10.00				11.60	0.14
6 Optical Effects of Dirt/Dust/F	0.20	0.20	0.10	0.20	0.10	X				0.80	0.01
7 0							X			0.00	0.00
8 0								X		0.00	0.00
9 0									X	0.00	0.00
COLUMN TOTALS	1.80	1.80	15.30	11.40	16.10	35.00	0.00	0.00	0.00	81.40	1.00

Technical risk

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	10.00	5.00	5.00	5.00				26.00	0.29
2 Intensity Harmony between	1.00	X	10.00	1.00	5.00	5.00				22.00	0.24
3 Sun Spots on Display (thoug	0.10	0.10	X	0.20	5.00	10.00				15.40	0.17
4 Side Rear View Mirror Opaci	0.20	1.00	5.00	X	5.00	5.00				16.20	0.18
5 Accuracy in Color Change Ic	0.20	0.20	0.20	0.20	X	10.00				10.80	0.12
6 Optical Effects of Dirt/Dust/F	0.20	0.20	0.10	0.20	0.10	X				0.80	0.01
7 0							X			0.00	0.00
8 0								X		0.00	0.00
9 0									X	0.00	0.00
COLUMN TOTALS	1.70	2.50	25.30	6.60	20.10	35.00	0.00	0.00	0.00	91.20	1.00

New development cost

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	5.00	1.00	5.00	1.00				13.00	0.20
2 Intensity Harmony between	1.00	X	5.00	1.00	5.00	1.00				13.00	0.20
3 Sun Spots on Display (thoug	0.20	0.20	X	0.20	1.00	10.00				11.60	0.18
4 Side Rear View Mirror Opaci	1.00	1.00	5.00	X	5.00	5.00				17.00	0.27
5 Accuracy in Color Change Ic	0.20	0.20	1.00	0.20	X	5.00				6.60	0.10
6 Optical Effects of Dirt/Dust/F	1.00	1.00	0.10	0.20	0.20	X				2.50	0.04
7 0							X			0.00	0.00
8 0								X		0.00	0.00
9 0									X	0.00	0.00
COLUMN TOTALS	3.40	3.40	16.10	2.60	16.20	22.00	0.00	0.00	0.00	63.70	1.00

Lead time

	1	2	3	4	5	6	7	8	9	TOTAL	DECIMAL VALUE
1 Colour Harmony between An	X	1.00	5.00	1.00	1.00	10.00				18.00	0.21
2 Intensity Harmony between	1.00	X	5.00	1.00	1.00	10.00				18.00	0.21
3 Sun Spots on Display (thoug	0.20	0.20	X	5.00	5.00	10.00				20.40	0.24
4 Side Rear View Mirror Opaci	1.00	1.00	0.20	X	5.00	10.00				17.20	0.20
5 Accuracy in Color Change Ic	1.00	1.00	0.20	0.20	X	10.00				12.40	0.14
6 Optical Effects of Dirt/Dust/F	0.10	0.10	0.10	0.10	0.10	X				0.50	0.01
7 0							X			0.00	0.00
8 0								X		0.00	0.00
9 0									X	0.00	0.00
COLUMN TOTALS	3.30	3.30	10.50	7.30	12.10	50.00	0.00	0.00	0.00	86.50	1.00

Table 5. Projects in line vs criteria weight matrix from table 4

For each one of the topics, there are 7 operative concerns (Table 4) matrix, where more data conforms the final indicator considering:

1. Ease of hardware change

2. Dimensions and configuration change

3. Reliability

4. Redesign complexity technical risk

5. New development cost

6. Lead time

Each of these 7 concerns are now analysed into each one of the topics in figure 15, as it is now shown in Table 5. Here the same scale values are assigned, as they were in the first matrix, 10 for "Much more value", 5 for "More Value", 1 for "Equal Value", .20 for "Less Value" and .10 for "Much Less Value". Finally, each topic from Colour Harmony to Optical Effects of Dirt, are compared with the criteria weight, throwing out a second set of data seen in *figure 16.*
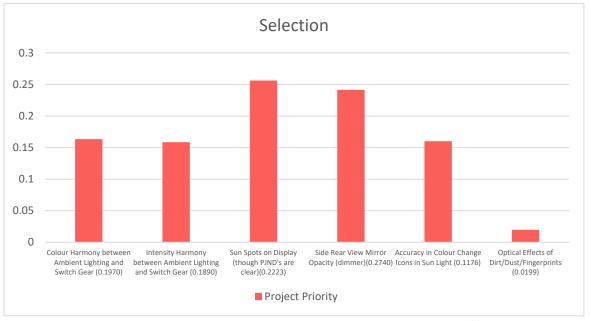
Figure 16. Table 5 project priority graph

In comparison, the second approach provides detailed qualitative data, thus more accurate decisions can be made after reviewing the attribute score, which will determine for example whether the new development cost or redesign complexity would have a higher priority, depending on the product development aims, which will define the project charter. In the lower figure, we can now determine how Sun Spots on Display has higher priority than the initial Side Rear View Mirror Opacity in the first criteria analysis, because now other factors or overall feasibility has been considered.

Selection

(Top chart — "Selection", Attribute Impact, y-axis 0 to 25)

Categories and values:
- Colour Harmony between Ambient Lighting and Switch Gear (18.2)
- Intensity Harmony between Ambient Lighting and Switch Gear (20.5)
- Sun Spots on Display (though PJND's are clear)(15.9)
- Side Rear View Mirror Opacity (dimmer)(22.7)
- Accuracy in Colour Change Icons in Sun Light (13.6)
- Optical Effects of Dirt/Dust/Fingerprints (9.1)

■ Attribute Impact

Selection

(Bottom chart — "Selection", Attribute Impact, y-axis 0 to 0.3)

Categories and values:
- Colour Harmony between Ambient Lighting and Switch Gear (0.1970)
- Intensity Harmony between Ambient Lighting and Switch Gear (0.1890)
- Sun Spots on Display (though PJND's are clear)(0.2223)
- Side Rear View Mirror Opacity (dimmer)(0.2740)
- Accuracy in Colour Change Icons in Sun Light (0.1176)
- Optical Effects of Dirt/Dust/Fingerprints (0.0199)

■ Attribute Impact

Figure 17. Criteria weight trade study & project priority graph comparison

3.1.3   Process Mapping

Based on DMAIC further than mapping every step of the process, it allows the alignment of the collected requirements to design relevant output improvements and ensure that the process capability and effectiveness remain uncompromised (Jones 2014).

To improve a process or indicator, there must be previous data available so the enhancement can be measured. It is necessary to review the optical failure mode process and sub-processes within

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it. Historical changes in the framework and complexity of process capability are often determinant in the project's performance, and it becomes of critical importance to have a clear picture of the procedures.

If we take the *Sunspots on Display* SOF, which according to the prioritisation matrix is the one with the highest impact within the Missed to Capture Failure Modes, DMAIC would be an optimal tool to visualise a high-level process and how it would benefit the customer. At the same time Suppliers, Inputs, Process, Outputs, Customers (SIPOC) can be applied to existing processes and exhibit elements of improvement, usually applied on the "Measure" stage in DMAIC.

These methods are important components of the methodology evaluation and enable the correlation of significant characteristics in the product development stages and the product issues and performance.

DMAIC can be applied in many different variants depending on the project's aims and details. In this case, it is applied focusing specifically on the visualisation and optical analysis workflow to better correlate the results with the actual product creation scheme. The complete DMAIC process to continuously improve the simulation process is described below *(figure 18).*

Let's take veiling glare as an example. The Define stage identifies the need of change, and will clearly state what is the problem to solve, how critical it is and how likely it is to sort out. Measure is all about defining actions and metrics with which we will assess the current process and will be the structure of the system function that provides the performance baseline. To explain this in simpler terms regarding veiling glare, there will already be a specification limit of an optimal, acceptable and not acceptable performance of the issue. With this reference, we already have a performance parameter to follow. Within this failure mode, the current process should be dissected to assess which areas could be improved by different means such as hardware improvement, methodology, data management, etc.

Analyse will determine in parameters how the current process is performing, locating root causes, how inputs affect outputs and how likely it is to optimise the resulting numbers into a more

effective operation. Again, in the figure below some examples of the tools used for analysing the process are given, such as fault tree analysis, where maybe the CAD data collection is very inefficient, due to obsolete data base browsing, or the material characterisation is still not available to run a simulation.

Improve refers to applying solutions to optimise the process. In our example, risks can be anticipated by having a checklist of the available data, systems needed versus readily available or software accuracy and time to run.

Control will ensure the improvement is maintained and continuously improved, by having a foresight of the new tools available to run a veiling glare simulation, having a control plan of how periodically new assessments will come into place and should monitor the running performance of each task (Staudter, et al. 2013).
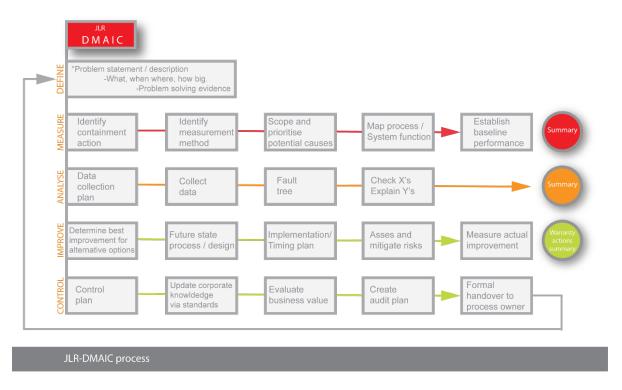
3.2   Discussion and Issues Identification

As mentioned before, historical data and previous parameters need to be in place in order to map an improvement of a process. It soon became evident DMAIC would not serve as the appropriate

approach if used as an optimisation tool looking to implement new technologies and workflows. It yielded far from the main objective of delivering an innovative solution using tools out of the actual working scheme. It also demanded a project-team effort, looking to improve an already well-established process to deliver an improvement within the running structure as it is, using the resources and means at present, and to establish new recommendations.

On the other hand, the SOF identification and priority matrix is useful to establish how pressing and hierarchically important the simulation test is in relation to others, depending on previously available data, traceability or issue similarities.

These aspects raised the acknowledgment that another approach needed to be taken from the early stages of the research, to tackle more cohesively an issue of new technology implementation and other means of visualisation in general, since the objective was never about improving the optical analysis per se, but to find better ways of visualising automotive lighting simulations with a reliable level of accuracy compared to a real scenario.

The Reflection Study presents itself as the most viable candidate to be benchmarked as the baseline analysis, which is a general visualisation assessment of the interior, providing the richest visual sample. This test is the most recurrent of all the systemic failure modes done throughout the automotive product lines, being the most fundamental specification fulfilment for optical performance and digital perceived quality assessment.

As it has been mentioned, there are several important failure tests such as PJND, which is represented in graphs, but the Reflection Study will shed a better understanding of the top-level visualisation benchmark. Other analyses mentioned before, provide in depth data regarding the specific optical performance issues, at different light conditions, and help to determine critical scenarios, but the reflection study ultimately represents the general visual interface which envelops the overall perception of the car interior.

4 The Research Question and Objectives

The research premise aims to clearly integrate visualisation as an essential component in product creation, not only as a design tool, but also as an integration instrument among various development departments to achieve better collaboration.

Visualisation, or more technically speaking modelling and communicating light in an NPD environment is currently a growing practice among many manufacturing industries, especially in automotive and aerospace sector. JLR Optical Inter-attribute team is currently evaluating various aspects within the optical quality assessment. Avoiding unwanted reflections, perceived quality verification or colour harmony are some of the topics being tested, among many other areas. An overview of virtual prototyping and lighting is shown int the figure below, where a general context is set *(figure 9)*.

4.1 Modelling and Communicating Light in New Product Development

These aspects range from concept design and aesthetics to engineering quality assurance. Each one of them with different inputs, processes and outputs, but commonly sharing the visualisation perspective.

Within this context, the need of testing virtual prototypes for design and engineering has largely grown in recent years, allowing engineers and managers to make accurate, timely and informed decisions without producing a physical prototype. Furthermore, the use of new visualisation techniques is in constant evolution offering a wide range of possibilities from High Dynamic Range (HDR) imaging to immersive environments, that are becoming more accurate in terms of optical performance and lighting accuracy, compared with real parameters, thus the need to implement new visualisation methodologies and technologies into the product lifecycle, especially in the development phase.

The diagram shows "Modelling & Communicating Light In Automotive NPD" as the central node connected to five branches:

Performance & Quality Evaluation (Issues Forecast)
- Evaluating new customer-focused technologies and their integration into vehicle design.
- Traditional buy-off procedures.
- Visual / optical performance testing
- Predicting visual / optical performance in design and optical modelling tools.

New Vehicle Technologies
- Market forces, competition and the need of implmenting faster new technologies.
- Unique driving environment challenges.
  - Driver distractions, workload management, usability, multitasking, satisfaction, etc.
- Premium sector – passenger technologies.

Aesthetic & Functional Design Properties Communication
- Static / dyanmic visualisation, immersive visualisation, photorealism, functional-realism.
- Communication, understanding, decision-making, current and future practices.
- Added value.

Modelling & Simulation In NPD
- Digital prototyping in automotive NPD. (Past, present and future)
- Modelling lighting in automotive design.
- What's currently possible (Hardware, software, etc.)

Ambient & Artificial Lighting In Automotive Design
- Evolution of automotive interiors and exteriors.
- Lighting, glazing, mirrors,etc.
- Use of artificial light in automotive interiors.
- Artificial lighting and the customers' perception of quality.

Figure 19 Modelling and communicating light in an automotive NPD context.

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4.2 Knowledge Gaps

An important characteristic to point out is that there is no visualisation literature approach from a comprehensive lifecycle perspective, starting from the workflow implementation and optimisation, to a collaborative solution for design review.

So far, visualisation & simulation and the NPD process have been studied in separate research lines, which must be necessarily linked as a single communication, development and management instrument, due to the new technologies capabilities and their implementation into the Enterprise Resource Planning (EPR) systems and PLM. The integration of immersive scenarios with state-of-the-art lighting simulation, presents itself as a highly capable tool, specifically in the product development phase.

The need for a constant new technology adoption scheme, capable of adapting to change and different project requirements plays an integral part of the in the product development capacity to react to the market, essential not only to remain competitive, but also to establish new trends and higher standards, delivering added-value drivers and enrich the brand's presence and customer experience. Moreover, there is a need to keep up with the technological improvements more than ever to remain competitive. The use of new visualisation technologies must not be overseen, but on the contrary, should be incentivised to improve development processes and enhance business performance.

PLM processes require a clear team and phase overlap, which relates to concurrent engineering and efficiency in resource use. Visualisation using new technologies in the NPD phase, is capable to link complex development structures and stakeholders as a single collaboration tool in combination with the product data available in the PLM software, giving more emphasis to the visualisation output, while keeping the information management available.

Currently, digital modelling is done with CATIA V5, which integrates virtual prototyping to the PLM database. ANSYS Speos, is used for the optical and lighting simulation, which is integrated as a CATIA V5 plug-in. Being stated that, this research will look further into other solutions to

integrate the PLM and data sets to other software and interfaces to expand the communication spectrum, looking for more effective technologies for design reviews and decision making. The use of Virtual (VR) and Augmented Reality (AR) technologies, are projected to be the next work frame and interface for design, collaboration and decision making in the next years.

4.3   Research Questions

The current optical simulation integration to new visualisation aids are still in development, but new methodologies and processes may anticipate to the new prospected scenario, where the optical analysis can be communicated with the use of VR. This could be included as part of the innovation system foresight (ISF) plan (Andersen and Andersen 2012), as a step forward in the technology implementation and innovation strategy.

After exploring the automotive considerations, literature review and the NPD context, 3 research questions were formulated:

1. How can the automotive industry benefit from implementing new immersive technologies in the early design phases?

2. What is the value of using simulation and visualisation outputs for decision-making and design review?

3. How can emerging visualisation technologies be validated and implemented into the NPD workflow, with a focus on improving user experience and time-cost-quality through the development process.

The research will synthesise the NPD optimisation through new visualisation technology and its adoption. In order to achieve a viable value creation process, the following objectives were formulated:

1. Develop new methods for visualising and communicating the simulated effects of lighting on vehicle interior design.

2. Improve the automotive visualisations creation process while maintaining lighting accuracy.

3. Establish a clear comparison between conventional optical simulation software and the latest generation of design visualisation software.

4. Verify accuracy and certainty of the digital automotive interior visualisation against a real-world scenario.

5. Deliver a qualitative analysis of the user experience insights as a value creation indicator for implementing immersive technologies for design review.

6. Establish recommendations for new visualisation technology adoption and design-process value creation.

5   Methodology

First, the explanatory case study will focus on the current JLR simulation method, against the new visualisation software. The aim is to establish a timeline referring to the use of resources and tasks concerning the Reflection Study, PJND and Design Review including perceived quality.

It is important to point out that Speos, which is a CIE certified software, is mostly used for optical analysis and light measurements, which would be its unique selling point (USP). Vred on the contrary is mostly focused on automotive visualisation achieving high rendering level and digital model navigation, while having the option of working with photometric parameters. Nevertheless, a comparison of the visual outputs will be formulated to corroborate Vred accuracy concerning visualisation.

Render comparison will consider time and resources employed to produce the images, as well as image quality concerning pixels, noise and tone management. Once the rendering comparison results are set, immersive visualisation outputs will be tested using the appropriate hardware and software. If successfully implemented, these visual outputs will then be tested in a trial, to measure the user experience and establish a how valuable each technology is for design review, according to the subjects' experience in different virtual scenarios.

Finally, a technology value proposition will define the viability for implementing the new technology and outputs in the product development process, considering TCQ and user experience, to further propose a change management and continuous technology improvement testing and adoption scheme, establishing a clear assessment of how seamlessly the integration of emerging visualisation technologies such as VR can be executed into the workflow.

In this sense, the aim is to increase certainty for decision makers and designers to have the best-informed choices in an early stage of the whole product engineering,

Although this study is highly focused on automotive lighting simulations and visualisation, from a high-level perspective it also looks to pave the way of establishing a practical methodology to

adopt new technology, especially when it has never been used before or could not be compared to an analogue situation. The use of immersive visualisation technologies are just some examples of the tools which can enable a better understanding of a current design on a specific project, improving knowledge management and the way certain design configurations are communicated.

The Systemic Optical Failure (SOF) modes visualisation are a viable example to enable a flexible scheme to adopt new immersive technologies and improve decision making. Design evaluation processes within JLR's PCDS (Product Creation and Delivery System) scheme could benefit from a new technology adoption procedure within the product development process, since technology escalates exponentially through time.

The research will focus on qualitative data collection and sampling, which will be mostly shaped with primary data coming from the research observations, experiments, simulations and trials. The visualisation trial which will measure the user experience, visual output and technology value, will collect data based on a questionnaire using 4 analyses techniques:

1. Semantic differential scale
2. Rating system
3. In Vivo coding analytical process for qualitative analysis
4. One-way ANOVA single factor

Secondary data will complement the findings, such as literature references and best practices. Because of the research's hands-on profile and working with JLR in its actual optical analysis issues, this exploration will initiate as an explanatory case study, in order to describe and analyse the current methodology and principle involved in in optical analysis & simulation. As a source of convergence, the Reflection Study and visualisation will be taken as the benchmark and broken down into parts to understand the complete roadmap for further improvement.

There were stages of extensive trial and error to achieve many of the steps involved in the workflow and visualisation methods, which will be referenced, but will not be analysed in depth since it was not considered crucially relevant for attaining the results. A general overview of the methodology can be seen in (*figure 20)* shown below.
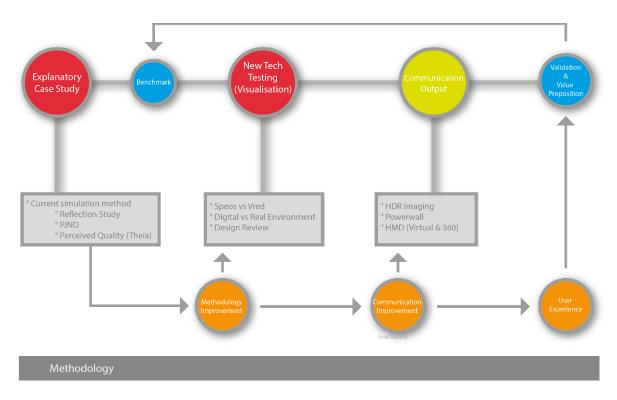
Figure 20. Methodology

Overall, the figure above shows the whole process, form the explanatory case study which will set the benchmark of how the current process stands in terms of testing and optical analyses outputs. After that, in order to propose a new technology, comparisons will be made between the current software package Speos and the proposed visualisation alternative Vred to state which is the most feasible tool in terms of visualisation, design review, perceived quality and collaboration. Afterwards, the best visual output will be running through an HDR display and imaging, powerwall and HMDs such as Oculus Go and HTC Vive.

These technologies will be assessed by JLR's highly trained engineers, which will provide their feedback regarding these technologies' value to the product development process and user experience. Finally, a value proposition will be formulated, which will corroborate or debunk the importance of new visualisation technologies integration into the product creation and engineering process. A more in-depth project plan is included in Appendix A, which explains in detail the whole project schedule and activities from beginning to end.

6 Optical Simulation Study and Visualisation Comparison

This chapter will focus on the workflow and visualisation comparison of two software packages: Speos and Vred. The first one is the current tool used by OCAE for the optical analysis and rendering. The second is the new selected software aimed to improve the visualisation output and its creation process. It also features photometric units and measurements, which enable designers and engineers to make a quick appraisal of the lighting situation and environment, while using real-lighting measurements.

A single Jaguar XE 2015 dataset acquired from JLR Teamcenter was used in both Speos and Vred software packages, featuring a complete bodywork with visible interior parts as the sample for what is called Reflection Study, which provides a rich visual preview of design configurations, textures, materials, undesired reflections, gloss and a variety of conditions upon different environments. It aims to show and detect any visual interference to the driving task.

But, before getting into the study, the data preparation will be described as part of the optimisation process. This is an important part of the dataset management and is critical for the TCQ improvement. Both scenes are set with the same geometries, high dynamic range imaging (HDRI) and emissive light sources such as in-vehicle displays and switch gear.

6.1 Data Preparation Workflow

The reflection study is set of SOF modes and is usually a default verification optical analysis which complies with the human-machine interface (HMI) requirements. In this case, Speos and VRED workflows are compared to establish an alternative process to improve the current TCQ. In the image below a general workflow roadmap is shown, describing the complete process form a raw dataset to the final visualisation outputs. Steps from 1 to 5 represent the data preparation stages ready to be simulated. Stages in blue show the different visual outputs. For each one of the steps timings were registered to have a record of the man-hours employed in each task *(figure 21)*.
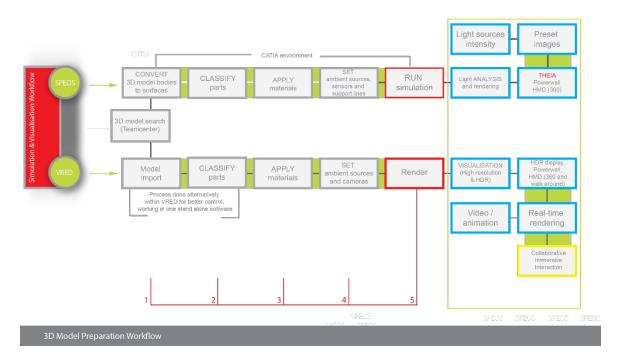
Figure 21. Data preparation workflow

6.1.1   Geometry setting and classification

Step 1 is one of the most time-consuming phases where the geometry optimisation and classification is made. Various steps take place at this point; for instance, the number of polygons must be reduced to the minimum possible, which becomes especially time consuming when working in CATIA and Speos, since geometries must be converted from solids into surfaces, while maintaining the mesh or surface quality. Since the optical properties are determined by the surface itself, later on, materials will determine the lighting behaviour and not the solid itself. Thus, the surface remains as the geometric critical factor which will determine the accuracy, although shape and integrity must be preserved by assigning stitching tolerance, chord deviation and tessellation quality available only in Vred import menu.

The geometry weight by itself is independent from the geometry vertices in this case (Iske, Quak and Floater 2002) and the mapping used in our lightweight geometry will determine the light data measurements.

When dealing with hundreds of parts, this task becomes almost painstakingly monotonous and a great deal of time is invested in a step that could be automated as it happens in Vred, which import options support the most common file extensions (Autodesk, Vred products 2019) and allows to tweak the polygon count and tessellation, which is crucial to keep a lightweight file while keeping geometry in detail. This is an import feature in the software package itself, and as mentioned before, it can be imported at different tessellation levels (Iske, Quak and Floater 2002). This stage shows a huge timing discrepancy due to this automated import tool, between Speos and Vred, which translates in man hours working just on importing the geometry, being significantly less on the latter being automated.

The time dedicated on the geometry conversion in CATIA, for a complete exterior body work and interior, summed up to 30 hours, which in a 37 weekly-working-hours-scheme, it translates into almost a week to complete, in particular due to the interior emissive parts such as switch gear, whose icons need to be offset individually, due to geometry inaccuracies and uniformity, while it is supposed to be arranged in separate bodies. This kind of inaccuracies are unlikely, but is a good example of adjustments needed to be made to run an accurate simulation.

In this case it is fair to acknowledge that it is not always necessary to have a complete geometry set to run a car interior simulation in Speos, but only the parts where light rays will have incidence or intervene in the optical assessment, nevertheless for this comparison, same conditions needed to be set, in order to have the same variables to the furthest extent.

In step 2, part classification, is very similar in both packages, since it's just about grouping parts to convenience, in the scene tree or geometry menu. Because of Vred capability of animating moving parts like doors, for design review, this grouping might take longer to assemble, but for now it will be referred as fixed geometry groups.

6.1.2 Material Characterisation and Application

Using the correct materials is crucial to achieve a precise optical analysis and a photo-realistic visualisation that portrays in a high level of detail of the product characteristics and attributes. It is one of the most important concerns in the data preparation phase, since it will completely drive the accuracy and quality of a simulation. As best practice, the ideal scenario is to work with digital materials scanned from physical samples with specialised scanners using a bidirectional reflectance distribution function (BRDF) (Nicodemus 1965), or gonioreflectometers. It is worth mentioning that some gonioreflectometers work with ".sbrdf" file extension (McAllister 2002) and is not supported by any of the simulation packages being reviewed in this study.

Nevertheless, material libraries have evolved to a high-quality standard, including the correct optical material properties such as diffusion, specular reflectance, roughness and refraction. The latest technology called micro-face BRDF accurately captures and reproduces surface reflection behaviour (Guarnera, et al. 2016). Both Speos and Vred, feature highly detailed material characterisation tools, where virtually any typical material can be replicated, and in general there are 4 main paths for implementing them:

1. By using default library materials for common textures (E.g. polycarbonate, glass or chrome)

2. By using specialised material scanners (OMS2, OCS, X-rite Total appearance capture TAC)

3. By creating it from scratch if the correct material parameters are available

4. By acquiring material libraries from certified suppliers (E.g. Substance, X-rite measured)

In the figure below (*figure 22*), an example of "JLR Ebony Windsor leather" (BRDF) material used in Speos, is replicated in Vred, and while both programs support a physical bidirectional reflectance distribution function (BRDF) file extension, it is not possible to import, since Vred supports only a special file extension called (.pbrdf). Speos Brdf materials where pre-set by Optis

directly to JLR material library, used in specific models. In any case, all material parameters were matched to recreate the same conditions. In generic materials such as ABS/PC plastics and leather which are isotropic materials, the variation was off by +/- 3 units, which was an indication of consistency between parameters through the material range for both material libraries *(figure 22)*. For anisotropic (Ngan, Durand and Matusik 2005)materials such as brushed aluminium and carpets, values from Speos BRDFs where taken as into generic VRED materials and matched as closely as the software parameters allow, to have the closest approximation of the BRDF material parameters in a close representation. In the end, this material approximation enabled the use of analytical BRDF materials with the same accuracy of the physical ones (Ngan, Durand and Matusik 2005).
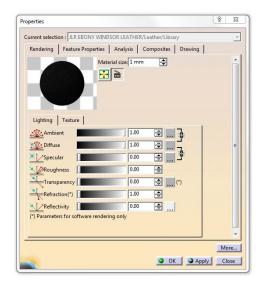
Figure 22. Material editors (Speos left, Vred right)
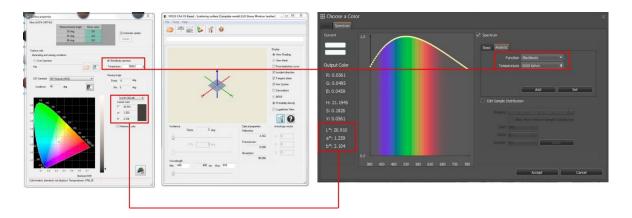
Figure 23. Speos and Vred material editors

The figure above shows how the material properties can be copied from Speos to Vred, adding the same values using CIE scale and LAB values as an analytic brdf file.

Within the workflow, having a well characterised material library enables to save a great deal of time applying the materials, although it is much more than a simple drag-and-drop action.

In Speos, there is a categorical differentiation of material assignment characteristics:

1. Volume optical properties (VOP), referring to propagation through solids.

2. Surface optical properties (SOP), concerning light rays' behaviour while hitting a surface.

3. Face optical properties (FOP), assigned to mirror and coating surfaces.

This study does not intend to go into detail of each property's function, but it is important to point out that the incorrect input can make the whole simulation go wrong or not work at all, so special attention is needed while preparing the model, and it may represent reviewing more than once all surfaces to reassure they are in the correct mode. In practical terms, these material modes are just a check mark on the material options, as FOP mode is generally applied to the car's canopy glass, and SOP means there is transmittance through the surface and propagation in its volume, so these are characteristics to be aware of while using SPEOS. These are non-existent in VRED and is completely controlled in the material parameters. In the end, with a complete material library, material assignment is very similar in both packages and straight forward.

6.1.3   Ambient Sources and Viewpoints

Sky light parameters have similarities between both software packages, although VRED presents extra features to represent the desired conditions within the user interface options, such as exposure.

Both packages can manage HDRI environments which acts as the scene light non-directional light source or natural light, setting it in 10,000 cd/m² as the default intensity, which is the benchmark for realistic lighting conditions in both software packages by default (*figure 24)*. There are also other default modes such as haze conditions, direct sunlight or specific light sources.
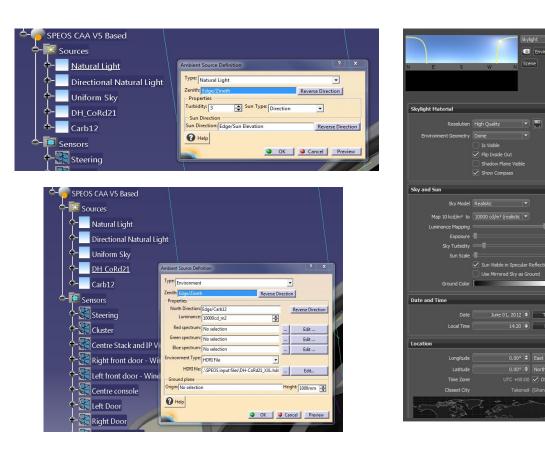
Emissive light sources such as display and switch gear, are also set with the desired lighting intensity and specification. For example, In the XE HLDF case, the display's emissive light intensity is set to 400 cd/m², but this will depend on the supplier specification. If the display is off, there is the

need to set the right material for specular characteristics, and direct glare, as it will be seen in a special study regarding display legibility, which assesses specular points that may interfere with the display's legibility. These are present when the display is on, but are put up to a limit failure mode to clearly verify such critical points.

Figure 25. Ambient sources and emissive sources

Viewpoints are determined by support lines extracted from the dataset and determined by human factors. The driver's centroid ellipse is set as the standard driver viewpoint for all simulations, and cameras are set in each of the view angles required. For the Reflection Study the spherical projection camera setting in Vred or the Immersive sensor in Speos allows to render in 360 degree, which can later be viewed on head mounted displays (HMD).

As it can be appreciated in *figure 25,* the CAD feature tree shows the arrangement of the all the different light sources available in the scene, from the ambient light source including luminance, sun angle and intensity, to the artificial light sources in the interior of the car, such as switchgear, ambient light guides and simulation scenes at the bottom, such as Centre Stack and Steering Wheel.

The time dedicated to set all sources and viewpoints is significantly higher in Speos, by almost double the time, 2 hours against 1, considering an experienced user, starting from scratch, without any preloaded reference points, and loading all lighting sources in the car interior. Ambient sources and HDRI environments are as important as the quality of the materials used in the model, so it is important to capture HDRIs in the highest possible resolution, set materials with realistic parameters and ensure that all data inputs are correct, since the quality of data will determine the best simulation output and visualisation.

Finally, at step 5, Run Simulation / Render, is where a huge difference arises (figure *26)*. The Speos simulation was set with 6 different ambient sources: direct light, directional natural light, uniform sky, and 3 different HDRIs, so there are 6 different simulations being calculated. It took 119 hours to render all scenes, which would be almost 20 hours per render. By the other hand, Vred produced renders from 13 min for a backplate and other 2 different skies, and 40 minutes for HDRI, producing the same images in nearly 3 hours. Even if there are no optical measurements in Vred, it is possible to have luminance and illuminance previews with intensity scales in cd/m^2 as it will later be shown in the Reflection Study.

It is also important to outline that Vred renderings were set to 4K resolution, while using Reinhard Luminance image processing, which is a tone reproduction algorithm for digital imaging (Reinhard, et al. 2002), which takes luminance values from each pixel and matches HDRI tone mapping, which is by far a superior image output (Faridul, et al. 2014) compared with the Speos images, which are plain rendering visualisations based uniquely on raytracing.
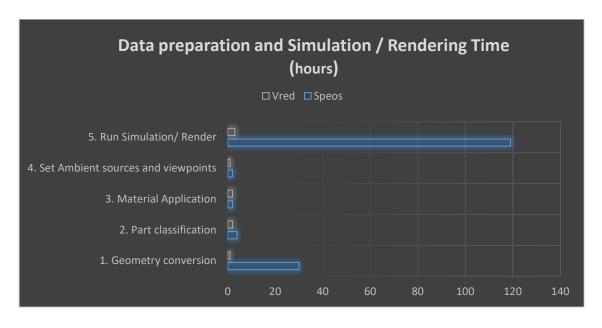
Figure 26. Data preparation and rendering time

6.2 Reflection Study, Veiling Glare and PJND

These set of optical studies and visualisations were first completed with the supervision of the OCAE team at JLR using Speos simulation software and complies with the HMI design verification methods (DVM). Afterwards all steps on the previous chapter were carried out and new Vred visualisations are set upon. The study focuses on the main aspects which may inhibit the driver's optimal view angles which include:

Interior Visibility	Issues
I Reflections from components and surfaces in DLO	Reflections of illuminated components in DLO
	Reflection of illuminated components in sideview mirror zone
	Reflections on glossy component in DLO
	Direct glare
	Cluster reflections
2 Veiling Glare	Gloss requirement
	Veiling glare assessment
	Zone identification
	Gloss measurement
3 PJND of light incidence to the interior	Infotainment screen

Table 6. Reflection SOF modes

6.2.1 Reflections from Components and Surfaces in Windscreen, Glossy Components in DLO and Direct Glare.

Reflection of illuminated components on DLO (Daylight Openings) verifies whether lighted components on the instrument panel (IP) or other areas in the vehicle interior reflect into the windshield zone C or in the outside mirror viewing zone of the door glasses. In this case the rendering shows all A, B and C areas in the windshield are clear, prioritising Zone C since it is the most important area of the drivers view.

Figure 27. Windshield zones

By performing a visual check at the windscreen (zone C) and modifying values by increasing contrast and brightness levels, it can be confirmed that no lighted components of the IP or other areas in vehicle interior reflect into the windshield zone C.

From the centroid of the viewpoint ellipse, no reflections from illuminated HLDF will occur on the X760 windscreen. From the centroid eyepoint there are no reflections from any light source or shiny reflections from materials.
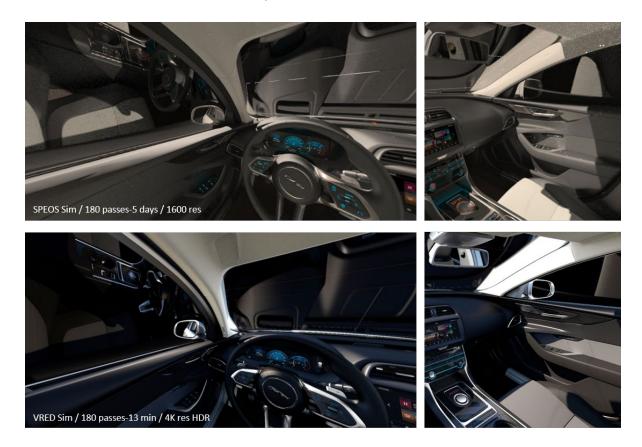
Element	Windscreen
Cluster	OK
HLDF	OK
Steering Wheel	OK

The reflection study is the first approach to visualising the lighting performance inside the car, and while comparing both visualisations, as a preliminary assessment and before subjecting the images to histograms and level values, same shadow patterns and reflections were observed, with the difference of Vred colouration being more vivid and presenting an increased number of highlights and contrast, due to the HDR tone mapping and the Reinhard luminance image processing. These tone mappings make a huge difference for design review, since image detail becomes significantly enhanced, making details bolder and noticeable, which is a significant advantage for design review.

At the same time, noise was significantly reduced in *chiaroscuro* (Robinson 1869) areas, which are high contrast compositions where light and dark zones are next to each other as it can be noticed in the A pillar lining and the passenger's seat against the carpet in *figure 28* above.

6.2.2 Reflection of Illuminated Components in Sideview Mirror Zone
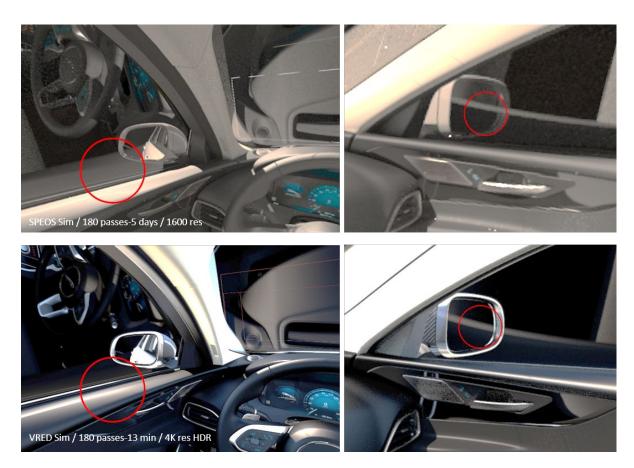
Element	Driver's mirror	Passenger's mirror
Cluster	OK	OK
HLDF	OK	OK
Steering Wheel	OK	OK
Door/Light Switches	OK	OK

Figure 29. No illuminated elements on side mirror zones

In the same manner, the centroid viewpoint is rotated to assess DLO and sideview mirror possible reflections. No illuminated components will reflect in the side view mirror for the driver side and passenger side.

6.2.3 Reflections of Glossy Components in DLO

Element	Left Mirror	Right Mirror	Windscreen
Left Vent Frame	Visible	OK	OK
Right Vent Frame	OK	OK	OK
Right Top Roll	OK	Visible	OK
Left Top Roll	Visible	Visible	OK

Figure 30. Gloss reflections on mirror zones

This specific visualisation is used to identify and assess reflections from interior parts' gloss into the side glass mirror zone *(figure 30)*. Gloss from the door top roll reflect unto the sideview mirrors' window area, which can cause distraction, especially on the right-side window. The left side reflection's opacity is lower compared to the right window. And yet again, the noise reduction is considerable in the Vred version, which is visibly apparent and can be quantified using the luminance image processing analysis *(figure 31),* visible on the roof lining.

6.2.4 Direct Glare
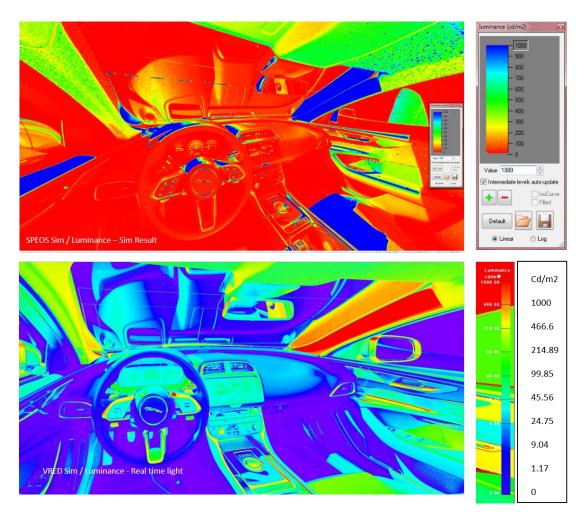
Figure 31 Driver's viewpoint in luminance image processing

Identify and assess specular reflection or glare from non-illuminated component to driver's eyes. Several interior glossy parts may generate direct glare to the driver and highlights are very similar in both images, where the A pillars, steering wheel inner frames and console linings appear to be the most reflecting elements. With this evidence it is possible to suggest that the ideal material tone to be used in the A pillars should be dark, but other aesthetic and design considerations are included. As it can be seen on the scales *(figure 31),* SPEOS reflections are shown in blue, while VRED's are shown in red, which shows inverted colours.
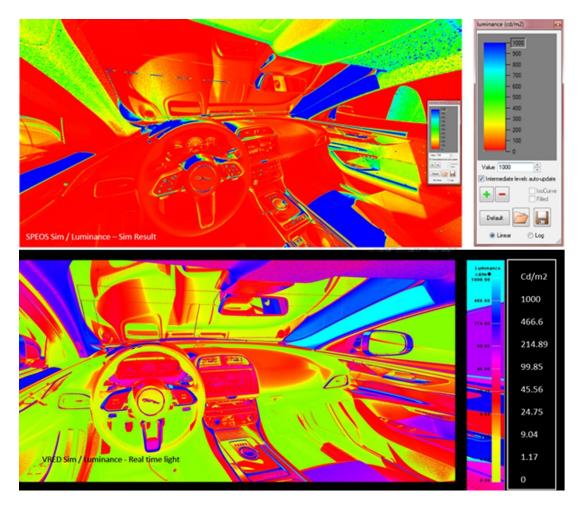
Figure 32. Driver's viewpoint in luminance image processing

Unfortunately, none of the software packages allow to change the colour scale for comparison reasons, but the image can be reworked with photographic software to rearrange the colour scale and match the colour gradient closer, where the blue colours emphasise high reflectivity. Taking a look at figure 31, and considering the Optical Principles discussed in Chapter 2.7, to have a reference of how intense cd/m^2 luminance, referring to *figure 5* shows the luminance values and scale. As an example, 400 cd/m^2 is the default luminance set to an IP infotainment system. So brushed aluminium on the steering wheel control frame shows to be around 600 cd/m^2, which might become a glare distraction in direct sunlight.
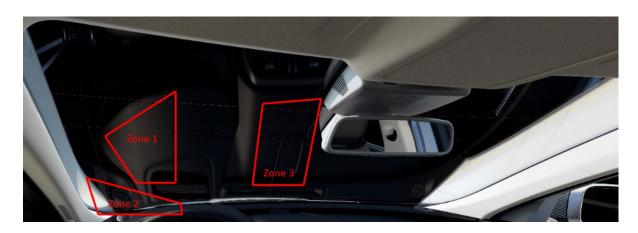
6.2.5 Veiling Glare

This method is measured through a radiance simulation sensor and natural sunlight without the sky.

Radiance measurements are not available in Vred, which again makes Speos the software of choice

for optical measurements and analysis. As seen in *figure 33,* there are 3 main critical zones that may

cause a visual hazard if reflections or ghost images reflect on the driver's eyesight.

Veiling glare and PJND methods are discussed to expose Vred limitations on optical analysis.

The actual method and calculation for these last couple on analyses will not be discussed in this study

since the main concern is the visualisation output and due to fact that these are methods developed

by JLR who is proprietary of this method of analysis.

VGI Zone	VGI result	Sun Angle
Zone 1	5.4	25
Zone 2	7.3	30
Zone 3	3.7	40
Windscreen rake at 63°		

Figure 33. Veiling glare zones and result

The VGI threshold for unacceptable reflectance is 30. The veiling glare analysis using a black

leather instrument panel (IP) is far below from the threshold, VGI index using a dark material is

located far below from the acceptable limit. Running the same test with a light colour IP, it VGI is

surpassed with Zone 1 value difference of 52.21 units as shown in *Table 7*.

VGI ZONE	MAXIMUM VGI RESULT	SUN Angle
VGI – Zone 1 Arabis expresso	5.04	**25**
VGI – Zone 2 Arabis expresso	7.16	**30**
VGI – Zone 3 Arabis expresso	3.54	**40**
VGI – Zone 1 Almond	51.67	**30**
VGI – Zone 2 Almond	77.21	**45**
VGI – Zone 3 Almond	**57.25**	**75**

Table 7. VGI Values with Arabis Expresso and Almond colours in IP

6.2.6   HLDF Performance and PJND Legibility

Identify and assess direct reflection or glare from the reflectivity of a component into occupant's eyes, showing the reflecting bodies through the eyesight path and possible distraction using a specular surface as the display.

10% of the HLDF surface reflecting day light openings (DLO) or light coming through glass.

13Deg ideal viewing angle with +/-10Deg admissible tolerance on a horizontal axis.

The blue driver's centroid number 1 would correspond to 0Deg to the screen's normal, while the yellow centroid number 2 represents 10Deg below the normal.
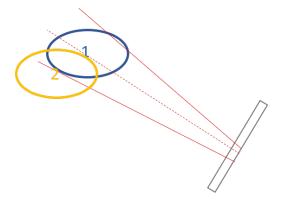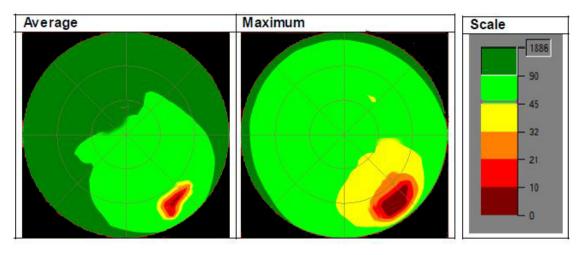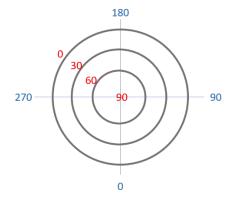
Figure 34. HLDF viewing angle

In *Figure 34* above, the 13 degrees represents the best HLDF or screen angle orientation towards the driver's centroid.

Perceived Noticeable Difference (PJND) on light reflections and instrument legibility through specific situations and environments refers to simulating how different sun angles interact with the car interior, from non-critical to risky situations, where the driver's instrument legibility may be affected by incoming light through the DLOs.

A PJND plot taken from excel design table shows the most critical sun angles for the driver's viewpoint towards the HLDF *(figure 35)*. These critical sun angles are represented by the red spots will come from the rear right side of the car. The PJND plot can be rendered step by step in both packages, showing the sunrise/sunset sequence in a frame by frame animation, which can very clearly represent the sunlight washing out the HLDF screen, which is ultimately the point of concern in this study.

PJND plot represent the position of the Sun in the sky and the target represents a view from the top of the car. Coordinates in blue refer to the Sun angle position relative to the car, while the red ones the Sun elevation, 90Deg being the Sun at the zenith point in the sky.

Figure 35. PJND critical sun angle mapping (JLR Research Report 9926620 02.2 2012)

6.3   Imaging Comparison

To reach a common ground of image comparison, Vred rendering is set using photometric

parameters and the Spectral Rendering is enabled, which according to Autodesk claims to accomplish

lighting simulation results:

> *"**Photometric Parameters:** Activates the photometrically consistent rendering pipeline to generate images containing realistic and reliable luminance information. The process chain includes photometric input values for light sources, environment maps, materials, cameras, clamping threshold and the display luminance. Spectral data for light sources and incandescence are photometrically consistent and physically implausible parameters are removed from the user interface. This mode provides the means to reproduce the rendering results with realistic luminance information on the display. Therefore, it is necessary to set up the display luminance parameter to match the current display, preferably using measured data. Also, the clamping threshold and the tone mapping parameters of the cameras are to be adjusted accordingly.*
>
> ***Spectral Rendering:** Activates the spectral rendering pipeline for Raytracing. The lighting simulation calculation will use spectral distributions for all the colors instead of conventional tristimulus RGB values. The spectral information for the color channels of materials and light sources can be provided and edited by opening the respective color dialogs."*

<div align="right">(Autodesk Inc. 2019)</div>

Moreover, the Speos Spectrum files were loaded in the scene to ensure the same

wavelengths and colour from emitting sources. In this section, 3 different visualisations are shown

next to their respective histograms.

1. Vred image of the driver's viewpoint with a physical camera image processing.

2. Vred image of driver's viewpoint with Reinhard luminance image processing.

3. Speos image of driver's viewpoint standard output.

The histograms of these images (figure36) show a very close tone distribution plot, with a

tendency to the low brightness due to the scene setup, which is necessary to assess light incidence

from a single source. The differences are determined by the light sensors (Speos) and camera

exposure and tone mapping (Vred). It was setup in a completely black environment, which allows to

capture only the highlights and illuminance happening in the car interior, being the reason why the

images seem underexposed. Being said that, the three histograms range are intended to be in the dark range, having slightly different brightness distributions. Overall, the images show poor use of the grayscale due to the low light conditions and the exposure, and slightly overexposed peaks on the right side of the graphs. Nevertheless, the graphs show consistency between the 3 visualisation outputs, with slight changes on the middle and brighter ranges. This responds positively to the premise that the simulation and visualisation software packages can be both reliable in terms of visualisation assessment, but with a huge resource use difference, which will be part of the final value proposition in Chapter 9.2.

Figure 36. Visualisation histograms

7 Real Environment vs Simulation Verification

This study attempts to exactly replicate a Jaguar XE 360 HDR photograph against a simulation environment generated in Vred, to verify how consistent a simulation render is, in terms of lighting accuracy and visual representation. At this point Speos was discarded as the visualisation tool, but this will be discussed in *Chapter 9.1 Research Results.*

7.1.1 Study Limitations

In this comparison, one of the most important topics is clear sky conditions image capture, which provides an elementary lighting impression, rather than a complex fingerprint or mapping of the sky, making it easier to match in a digital environment. Due to schedule constraints and weather conditions, it was only possible to register partially sunny images. Luckily enough, there were direct sunlight windows in the photo shooting session, allowing to capture some shadow casting and stronger reflections.

Another issue would be to match the HDRI environment light taken at (*x*) time with the lighting captured at (y) time inside the car. A possibility would be to shoot at the same time the environment and the car interior images, but not even with two cameras would be possible to capture the exact same spot.

7.1.2 Method and Setup

A Jaguar XE 360 interior real image is compared with a VRED 360 rendering. Both images using same environment conditions, HMI centroid as common viewpoint, and material characterisation taken from JLR's BRDFs material definitions, previously used in the simulations.

7.1.3 Environment

The location and environmental conditions are registered at the exact geographical coordinates, day, shooting time of each photograph and even humidity and atmospheric pressure, which is a topic that will further be considered in *Chapter 11 Discussion.*

360 Environment Conditions	
Location	52° 56' 54"N 1° 10' 53"W
Date	August 29th, 2018
Time	14:07
Weather conditions	Partly sunny Humidity 64% 1015 mbar
Wind speed	10 mph
Camera lens direction	235° SW
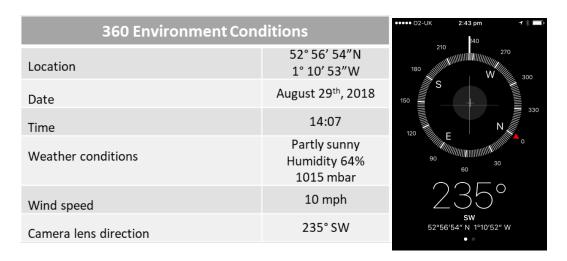
Table 8. 360 Environment conditions and camera direction

The exact orientation was first determined by marking the tripod's position and camera direction in a feasible frame shot, to later park the vehicle matching the driver's centroid view, and the camera lens position and direction.
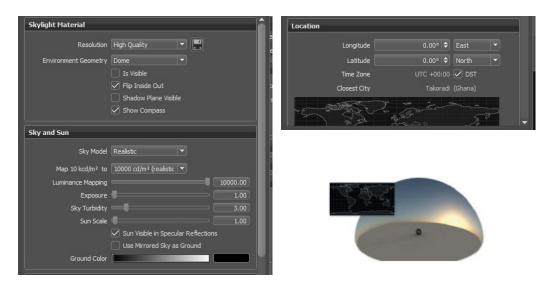
Figure 37. Simulation environment conditions setup

A custom-made rig specifically adapted for Ricoh Theta (Appendix H) 360 camera was mounted from the car's ceiling using the headrest centre-to-centroid distance, ceiling-to-centroid normal distance in a vertical line and steering wheel-to-centroid distance as main parameters, plus other secondary distance references to properly match the centroid location at the camera lenses, as it is shown in (*figure 38*).

Figure 38. Camera mount rig for Ricoh Theta

Ricoh Theta V 360 camera settings were determined by the lighting conditions at the time of each photo shot. Again, it is needed to stress out that although it was possible to take pictures with direct sunlight, the sky cloudiness represented a difficult condition to virtually replicate.
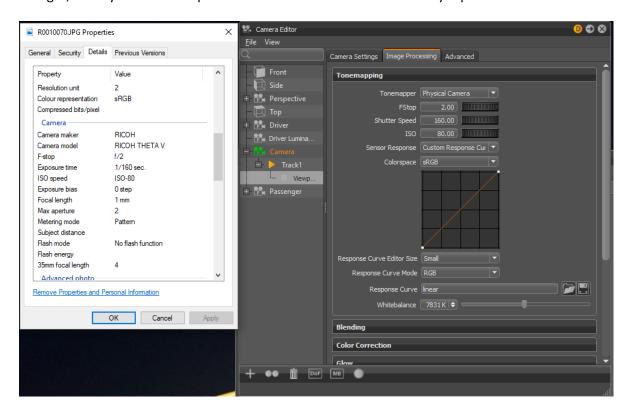
Figure 39. Physical and virtual camera settings

Cameras' settings feature the main shot parameters such as F-stop, exposure time and iso speed, but Ricoh's camera CMOS sensor may have a different image processing that may vary from Vred's. Even in comparison of physical cameras such as Cannon and Nikon, there is always a slight variation in colour and contrast, due to the sensor's characteristics such as size, sensitivity or light capturing. The exact specification for both is not available, and must be considered as an uncertain variable, which should be tested in the future, having the potential of resulting in colorimetry variation. It is possible to match in post-production, but this will completely miss the goal of objectively comparing the visual output between them, although it may be a valuable topic to further

study based on colour calibration on different systems such as Munsell, Ostwald, Rood or Titchener.

(Cochrane 2014)

7.1.3.3   Image Output Resolution
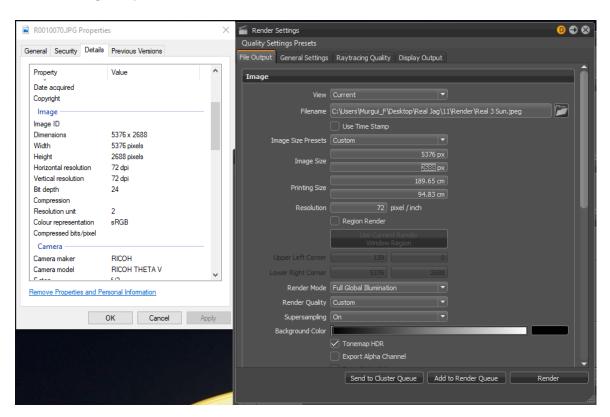
Figure 40. Image output resolution (Physical and Virtual)

Figure 41. Test setup

Both cameras were set with the same parameters as at the top of *figure 41,* with a size of 5376 x 2688 pixels @ 72 dpi of resolution, both using HDR tone mapping in an RGB colour model. For compatibility usage, both ".jpeg" and ".hdr" formats where saved, to be able to run these visualisation in HDR displays and regular platforms than not necessarily support HDR formats.

7.1.3.4   HDRI Generation
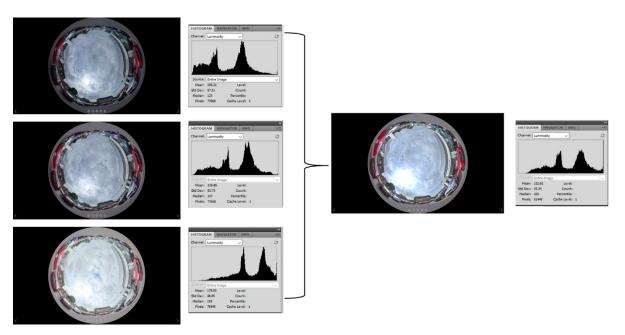
Figure 42. HDRI 360 environment generation

Ricoh camera features an HDR imaging option, but as mentioned before, the quality of the inputs will drastically determine the outputs. In this case it was decided to take 3 different exposure shots (-1, 0, +1) and then merge them into a .tiff file to obtain the maximum range of brightness and contrast in a single image. In other words, the HDRI sample was manually composed by combining three different exposures in one image, to ensure simulation scene runs with the best inputs available, ensuring the image quality integrity, rather than relying on the camera's HDR automatic output.

7.1.4   Visualisations and Results

Figure 43. 360° photo at the top. 360° simulation at the bottom

Jaguar XE 360
photograph

Jaguar XE 360
simulation

Figure 44. 360 Photograph vs Simulation

Figure 45. Luminosity and colour histograms

7.1.4.2   Inverse Imaging Histogram

Luminosity
Histogram

Inverse 360 photograph

Inverse 360 simulation
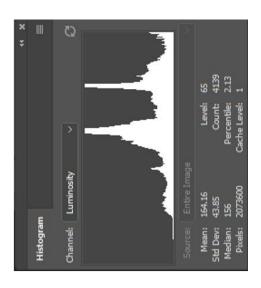
Figure 46. Inverse Colour Imaging

In figure 43 above, the 360-simulation image is shown right below the real 360-photograph. As mentioned before in this chapter, in both scenarios, the inputs where set to match as close as possible between them, including camera settings, materials, location and time. There where elements within the car models that where simply impossible to match at this point, such as missing parts like seat belts, safety handles, sun visors and even slightly different steering wheels. Other than that, the rest of the digital geometry and physical parts are an exact match including the material characterisation, which was previously set in the Reflection Study.

A very important factor to stand out in the simulation is the use of the HDRI + Skylight environments. The HDRI (*figure 42*) provided the environment light, while the Skylight *(figure 37)* projected the Sun light source to generate shadows coming from the model's geometry. In this way, the sun light source would exactly match the HDRI's brightest point, creating a composite image of environment + light source. At the same time the Reinhard tone mapping and HDR capability aims to achieve the most accurate image in terms of the HVS. A visual information quality assessment is based in objective and subjective criteria (Beghdadi, et al. 2013). This study takes advantage of the objective evaluation tools available such as tone mapping, HDR capability, noise filtering, compression, etc., to support the subjective perceptual evaluation and communication (Beghdadi, et al. 2013). Thus, the pursue for an accurate representation of a real scenario, becomes critical to evaluate the Visualisation Trial in the next chapter.

By looking at the luminosity histograms in *figure 45,* there are strong similarities in the curve, but it is noticeable right away that they are far from being identical. For instance, the photograph shows a more balanced exposition having the bright and obscure peaks towards the centre, while the simulation is slightly positioned to the left, representing a darker image, even though it shows a higher weight on the bright tones.

Moreover, the colour histogram shows a complete mismatch which at this point could be the result of unmatched material characterisation, camera sensor, real cloudy conditions against sky turbidity setup in the simulation or tone mapping, just to mention a few.

The later in itself covers numerous studies (Yoshida, et al. 2005) and represents a huge variation in colour, contrast, brightness and detail depending on its output, but considering the general perceptual attributes of an image such as brightness, contrast, colour reproduction and detail (Cadik, et al. 2007), an overall image quality can be considered to evaluate these attributes.

Although the colour match missed the mark, the simulation image levels and details in terms of lighting, shadows and contrast, provide a valuable tool in the product development process, and even though the visual representation is not a 100% depiction match of the real photograph, it does provide a functional realism (Ferwerda 2003) image, feasible for design and engineering simulation assessment purposes .

8   Visual Outputs and Technology Adoption

After analysing the visualisation workflow and simulation capabilities, the next step is to evaluate how to make the most of the visual outputs through different visualisation means, keeping in mind its integration into the product development scheme, added value if there is one and how the user interacts with these technologies.

After evaluating which would be the best visualisation software solution, Vred was selected for its communication and processing features, supporting: powerwall, HMDs, HDR luminance mapping output, real-time rendering, photometric parameters, collaborative sessions and presentation tools for design review. Theia was also considered, but lacked the array of tools, display support and user flexibility provided by VRED. A deeper analysis will be presented in *Chapter 9 Research Results.*

According to the software capabilities, 3 visualisation outputs were selected to test the visual experience:

1. SIM2 HDR monitor, which supports view of HDR and EXR imaging.

2. HTC VIVE HMD, for 360 imaging and full virtual scene experience.

3. Powerwall, for design reviews in stereo and tracked mode.

Then a pilot trial was devised, using the previous Jaguar XE images for continuity. The purpose of this trial aimed to shape and refine a final version which would be tested with JLR engineers, directly involved with visualisation, human factors, HMI and packaging.

This pilot trial protocol included 9 PhD researchers and 6 engineering professionals, who are related to visualisation activities on their daily work. They were presented with a car interior visualisation transitioning between 3 scenarios with different lighting conditions and environments. In the end, they were subjected to answer a 16 semantic differential rating question feedback sheet. which later on this research helped to shaped the first part of the final trial version in Chapter 8.3.1. Initially, this trial included the powerwall instead of the Oculus Go, by looking only at 360 imaging

rather than the immersive headset experience, as it can be seen in *Chapter 8.2 Visualisation Trial*.

Appendix C fully describes the final protocol.

The pilot's results are presented as an introduction to JLR Visualisation Trial. Overall, the response was very favourable for question 1, Visual Experience and question 15, Technology Adoption Willingness *(figures 47 & 48)*, which provided a practical insight of the proposed technology value and users willingness to try new technologies. Other insights taken to refine the final version, was the fact that using an HMD becomes an individual experience, unless the software is properly configured to work in a collaborative environment and look at the model with several HMDs, even from distant locations. In the other hand, stereoscopic vison and tracking is limited to one person's perspective and makes it hard for other participants to have a proper view. Multiple-user interaction is one of the key features that makes working in a virtual environment a significant tool for the technological value proposition.

Later, it was realised it should be first tested at an individual level, to later scale it up to a multi-user environment in a further study.

8.1 Pilot WMG Visualisation Trial. Shaping JLR's Trial.
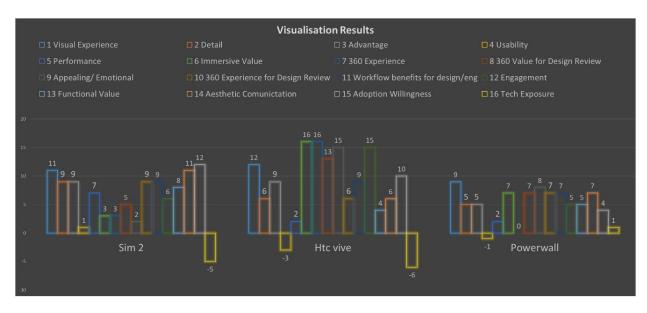
Figure 47. Pilot Visualisation Trial Results
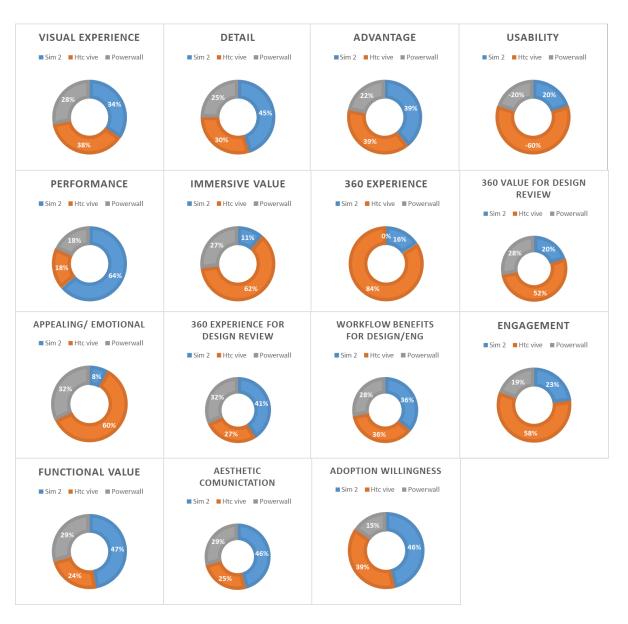
Figure 48. Pilot Visualisation Trial distribution results

Overall, the HTC Vive showed the boldest results regarding Usability, Immersive Value, 360 experience, Value for Design Review, Appealing / Emotional perception and Engagement *(figure 48)*. If this is compared against the last question 16 *(figure47),* regarding the Technology Exposure, it is quite evident that Sim2 display and HTC Vive have not been used by any of the subjects, even though the technologies are available for them. By looking at these preliminary scores, it can be implied that engineers find value in the use of these technologies, but don't necessarily have the means to

produce visualisation material for these platforms or consume this kind media in general, which is growing in the main stream market (de Regt, Barnes and Plangger 2020). Thus, the necessity of creating new workflows to generate visualisation content and ways of communicating data in a more engaging and valuable way.

The pilot also showed, that in order to have more insightful results, the need for going further from the rating system was required to capture these technologies' design, engineering and communication value.

These results were the first approach to defining each question's significance and further useful meaning for the final version. The full questionnaire can be consulted in *Appendix A.* It was included as a preliminary approach, to show how JLR's trial was finally formulated.

8.2 Visualisation Trial

8.2.1 Introduction

The aim of the Visualisation Trial is to measure the overall added value and feasibility visualisation tools and immersive technologies deliver to the NPD process. As new in-vehicle technologies are created and developed into products, consideration must be given to how the customer will interact with the technologies, and what influence ambient light will have on the interaction process. Being able to simulate, predict, and understand the visual interaction process between the vehicle interior, the ambient light, and the customer, is critical for optimising the design.

8.2.2 Objectives

a) Develop methods for visualising and communicating the simulated effects of lighting on vehicle interior design and new in-vehicle technologies, while selecting the appropriate hardware and software tools to optimise the communication of vehicle interior simulations, and the determination of where these tools can best be utilised to deliver the most efficient technology/product

development process possible, establishing a clear assessment of how seamlessly the integration of emerging visualisation technologies such as VR and AR can be executed into NPD methodologies. More specifically, this integration will be focused on lighting simulations and its visualisation at different levels in order to establish the level of certainty for decision makers and designers to have the best confidence and informed choices in an early stage of the whole product engineering. This should be accomplished by analysing the current processes (product lifecycle, NPD, etc.) in comparison with new technologies applied for process optimisation.

b) Achieve a high level of lighting accuracy comparable with reality and how to communicate it in the most efficient way.

c) To establish a methodology to mitigate the Systemic Optical Failure (SOF) modes such as *veiling glare* and enable the flexibility to be adapted to new immersive technologies and its implementation, in order to improve the decision making and design evaluation processes within JLR's PCDS (Product Creation and Delivery System) scheme.

d) To develop a new technology adoption procedure within the product development scheme, since technology escalates exponentially through time with new hardware and software. To keep up with more efficient tools, and continuously optimise time to market, quality and cost, through the implementation of a versatile workflow structure.

e) By testing different visualisation outputs, the user will provide feedback of the visualisation experience with the latest visualisation tools. The value proposition of each technology will be rated and finally allocated to the use of resources through the process and most efficient workflow implementation, to determine an integral value proposition.

8.2.3   Design Methodology

This is a qualitative prospective study divided in 2 parts, where the visualisation outputs are being tested through the observer's perception and experience, using 4 different visual outputs: Samsung UE850, Sim2 HDR47, Oculus Go and HTC VIVE *(Table 9)*. The benchmark (Samsung monitor), a regular

PC monitor, represents the visual tool used in a daily basis. Next, the subject will look at this same visualisation through the Sim2 HDR monitor, enabled with Emerald software, which provides a true HDR visualisation through an EXR file. After using the HDR display, the same media will be shown through Oculus Go HMD and finally, this visualisation will run through HTC Vive.

Specification	Samsung UE850	SIM2 HDR47	HTC VIVE	Oculus Go
	Benchmark			
Type	28" LED backlit LCD	48" LCD TFT + LED BLU + HDR	VR HMD dual AMOLED 3.6". Field of view 110 degrees	Dual JVC D-ILA Ultra High Resolution
Resolution	Full HD 3840 x 2160	Full HD 1920 x 1080	1080 x 1200 per eye (2160 x 1200 combined)	1280 x 1440 per eye 2560 x 1440
ANSI Contrast Ratio	1000:1	15,000:1		
ON/OFF Contrast Ratio	2,000,000:1	4,000,000:1		
Colour Temperature	5000K, 6500K, 9300K	5000K, 6500K, 7500K		
Brightness	370 nits cd/m²	2300 nits cd/m²		
Colour Depth	1.07 billion colours	68 billion colours		

Table 9. Visual Output Specification

While still wearing HTC Vive headset, the subject will interact in a full virtual environment, rather than just a 360-image, where the participant can experience a full interaction with the 3D model and scene, previously setup with the simulation elements, providing a higher level of interaction *(figure 49).*

Visual Output
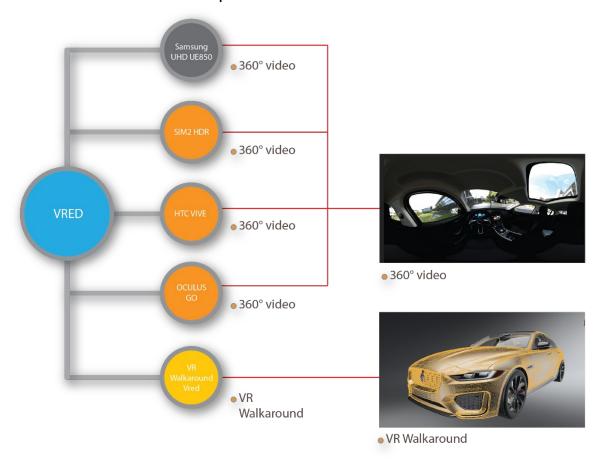
Figure 49. Visual output testing order

The 360-video used in the trial, can be seen in the following link:

https://www.youtube.com/watch?v=tPkKhElo-OM (Murguía, Sim Environments 2018)

8.2.3.1   Visualisation Trial Part 1

VRED visualisations are presented through four different display outputs, taking a 4K PC monitor (Samsung UHD UE850) as a benchmark *(Table 9)*, and participants will rate each experience and how valuable it is for the new product development process using a semantic differential scale to rate:

0 SAME (not better or worse)

1 SLIGHTLY BETTER

2 QUITE BETTER

3 EXTREMELY BETTER

-1 SLIGHTLY WORSE

-2 QUITE WORSE

-3 EXTREMELY WORSE

This rating scale above, will be submitted for each one of these questions:

Part 1 Questions Info Sheet	Explanation
Visual experience	Subject's visual perception towards a determined visual output over benchmark
Image detail	Refers to resolution and image sharpness over benchmark
Advantage over benchmark	How better or worse the output is for design review over benchmark
Usability	Ease of use and practicality over benchmark
Visual performance	Refers to brightness, contrast, and colour depth benefit for design review over benchmark
Immersive value	Level of immersive benefit for design review over benchmark
User experience	Overall usability
Value for design review	Benefit for design review over benchmark
Appeal / Emotion	Sense of realism and immersive impact on the senses over benchmark
Tech. benefit on workflow	How beneficial the technology is for displaying CAD, designs and simulations
Engagement level	How enjoyable the output is over benchmark
Functional value	How useful it is over benchmark
Aesthetic communication value	How visually appealing it is for design review over benchmark

Figure 50. Questionnaire Part

8.2.3.2   Visualisation Trial Part 2

In the last section of Part 2, answers 17-25 *(Table 10)* will be analysed through In Vivo coding analytical process for qualitative analysis and use of constant comparative technique to spot similarities and differences, coherence and incoherence within categories, relevance and alternative conceivable categories (Miles 1994). The code category was assessed by two other piers to verify unbiased allocation to each of the responses.

	Part 2 Questions Info Sheet
Tech Adoption Likelihood	14 If you were/are the decision maker, how likely would you adopt this technology?
Exposure to Tech	15 What is the level of exposure you have had to each technology in the past?
NPD Process	16 Rank each visual output according to each product development phase, 4 being the best option and 1 as the worst of them.
Coding figure	17 Do you think the immersive tools would offer more value than the current ones?
Coding figure	18 If yes, in which way would they provide this value or benefit?
Coding figure	19 How would you like to see these tools deployed and integrated into JLR's engineering process?
Coding figure	20 If you don't think they would be useful, do you think future, enhanced versions would offer this value / benefit? Why?
Coding figure	21 Do you know other people within JLR who could benefit from these technologies?
Coding figure	22 Would you recommend the use of HMDs to colleagues?
Coding figure	23 Would you be confident using VR hardware in an office environment? (e.g. wearing an HMD next to your colleagues)
Coding figure	24 Would you be confident to use VR equipment and run your own tests in this environment?
Coding figure	25 Comments or observations concerning the use of each output for the Technology Value Proposition in the new product development process.

Table 10. Questionnaire Part 2.

8.2.3.3   Materials, Procedure and Stimuli

The Visualisation Trial took place at JLR's Gaydon Design and Engineering Centre (GDEC) and hosted by Paul Hetherington, Visualisation and Immersive Development group leader. All the necessary equipment was taken into a dedicated office room, where the Uceri professional illuminance meter using CIE photopic spectral response, measured 324 Lux, which falls into the regular office light levels range.

The benchmark will be a 28-inch Samsung UE850 monitor, Full HD (3840x2160) resolution, calibrated with the regular Windows tool available in the control panel. The same procedure was applied to SIM2, but set at medium brightness setting. For the headsets, Oculus Go and HTC Vive were set to be used with the subject being seated. When the VR walkaround started, the participants were limited to stand, but not to walk around more than 3 steps from the initial spot.

The subject will then complete a questionnaire where he/she will rate the visual outputs and give final comments and observations. Visualisations take 2 minutes 40 seconds, (40 seconds per display), where a video with different lighting conditions of a virtual Jaguar XE will be

displayed as the example above in *figure 51*. In this section, the subject will be submitted to the VR walkaround which will be addressed as "Full VR Experience" to clearly differentiate it from the 360 footage.

8.2.3.4   Participants

The sample was integrated by 30 JLR engineers from 3 different departments within the Virtual Innovation Centre (VIC): OCAE team, which has collaborated throughout this research from the beginning, Human Factors team and Vehicle Packaging team. The list of participants is shown below in *table 11* and is included in *Appendix G.*

No subjects with special considerations such as pregnant women, motions sickness or even colour blindness are expected to participate in the trials. It will be asked if the participants have any special conditions, and if so, he or she will be asked not to take part in the trial to avoid any risk.

	Subject	Age	Role	Engineering purpose for visualisation technology	Purpose
1			Vehicle Packaging		Vision comparisons
2			Interior Vehicle packaging	Package investigation/ HF, ext vision, etc.	Geometry visualisation, vision studies, etc.
3			Human factors PAT Leader	Speos	Vision, pano roof
4			Vehicle Packaging Zone Leader	Package + Ergo	Vision, ergo reviews
5			Packaging	Interior roominess	Interior roominess evaluation
6					
7			Human Factors Specialist	Requirement validation and product development	Vision
8			UP Package Engineering	Geometry review / Customer use cases / Ext. loading / Trunk	Exterior vision / Geometry review
9			Human Factors Engineering	Assessment & Verification	Vision assessments / Packaging
10			Optical CAE Specialist	Optical review	Manufacturing and packaging
11			Vehicle Packaging	Benchmarking / Understanding of designs	Design reviews / Benchmarking user experience
12					
13			Human Factors	Feature demos	Intro session to department
14			Virtual Reality Engineer (CAVE)	Engineering support	I run it !
15			Subject Matter Expert (for vision)	Assess exterior vision	Exterior vision
16	C O N F I D E N T I A L		Human Factors SME	Commodity development and evaluation	Reviews / Evaluation / HMI prototyping
17			Human Factors Practicality SME	Console layout / Visibility / Practicality assessments	Practicality assessments
18			OCAE Engineer		
19			OCAE Analyst	Optical quality check	To compare SPEOS result with visualisation
20			Optical CAE Lead	Optical failure identification	
21			Optical CAE		
22			Human factors PAT	Surface assessments, vision, glare, DLU	Vision and practicality reviews
23			Human Factors Physical Usability SME		Assess rim block
24			Package Engineer	Overall vision	Vision
25			Lighting PRE P.S. Int/Ext	Assessing interior illumination and visual night drives	Working on a project with the V.I.D. team
26			Package Team Leader	Vision / Ergo	Vision
27			Virtual Visualisation Engineer	Central team for visualisation capability	Immersive CAD visualisation
28			Technologist		Testing / review
29			Human Factors Lead	Reflection assessment / veiling glare	Surface reviews / All around vision
30			Human Factors SME	Roominess SME	Vision / roominess assessment
31			Human Factors Specialist	Vision reviews, ergonomic comparisons	Vision reviews

Table 11. Visualisation Trial participants list

The invitation was completely open for people who want to get to participate in these trials and no obligation in taking part was expected.

8.3 Initial Results and Data Analysis

The final rating numbers were then analysed through one-way ANOVA (analysis of variance) single factor to produce relevant statistical figures such P-value, standard deviation, average rating and variance.

The first question was taken as an example to explain the meaning of each result for better comprehension of the analysis. Each of the questions were explained in a "Questions information sheet" *(figure 50)*, Appendix E where the subject can review the exact meaning of what is inferred in each question. E.g. "Visual Experience", refers to how the subject's visual perception compared to the benchmark.

8.3.1 Part 1

<u>1.Visual Experience</u>

VISUAL EXPERIENCE Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	60	2	0
OCULUS GO	30	60	2	0.62
HTC VIVE	30	61	2.03	1.55

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.02	2	0.01	0.02	0.98	3.10
Within Groups	62.97	87	0.72			
Total	62.99	89				
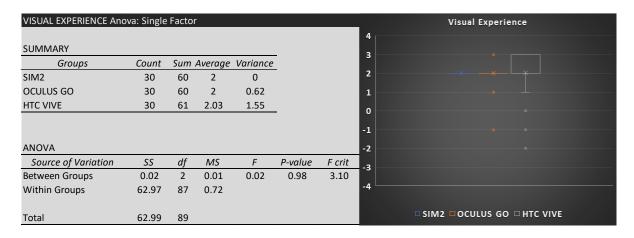
Table 12. Visual Experience

HTC Vive, despite having the lowest resolution, scored highest as an overall visual experience, but also had opposite responses, with some of the participants rating it as low as -2.

2.Image Detail

IMAGE DETAIL Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	44	1.47	1.09		
OCULUS GO	30	45	1.5	2.05		
HTC VIVE	30	21	0.7	3.18		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.29	2	6.14	2.917	0.059	3.10
Within Groups	183.27	87	2.11			
Total	195.56	89				
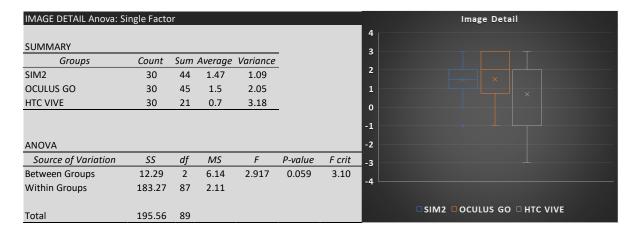
Table 13. Image detail

Refers to resolution and how clear can the small objects such as the switch gear can be distinguished. Sim2 was the most consistent, with 1.09 variance, but some subjects rated the Oculus Go as high as +3. HTC Vive shows divided opinions with an average spread between +2 and -1.

3.Advantage over benchmark

ADVANTAGE OVER BENCHMARK Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	34	1.13	0.88		
OCULUS GO	30	56	1.87	0.74		
HTC VIVE	30	52	1.73	2.41		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	9.16	2	4.58	3.41	0.038	3.10
Within Groups	116.8	87	1.34			
Total	125.96	89				
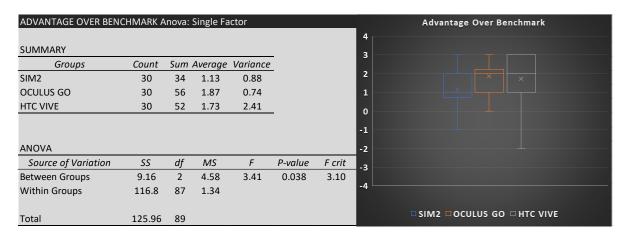
Table 14. Advantage over benchmark

The advantage of using all these devices was clearly positive overall, but again a huge variance number appears on the HTC Vive, while the other 2 devices showed a positive consistency.

4.Usability

USABILITY Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	10	0.33	0.44		
OCULUS GO	30	18	0.6	1.77		
HTC VIVE	30	21	0.7	3.045		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.16	2	1.08	0.62	0.54	3.10
Within Groups	152.17	87	1.75			
Total	154.32	89				
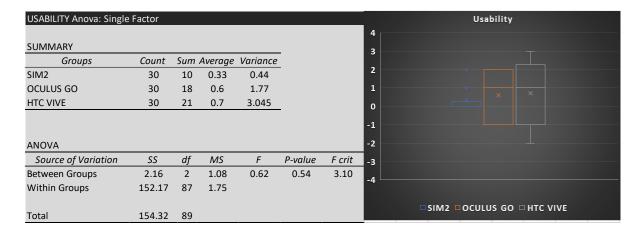
Table 15. Usability

Sim2 did not present much different opinions from a regular monitor in terms of usability, as the subjects found it all set up with an EXR file running through Emerald software, nor were informed it is transported on a case the size of a bar. For practical purposes, regarding the image and operation, it shows some positive ratings up to +2 points. On the other hand, the headsets had divided opinions, tending overall to the positive side. Again, HTC Vive shows a huge variance of divided opinions.

5.Visual Performance

VISUAL PERFORMANCE Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	46	1.53	1.50		
OCULUS GO	30	48	1.6	1.70		
HTC VIVE	30	34	1.13	2.26		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.82	2	1.91	1.05	0.35	3.10
Within Groups	158.13	87	1.82			
Total	161.96	89				
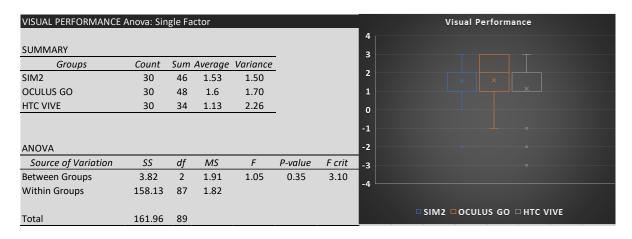
Table 16. Visual performance

The intent of this question is to look for the subject's overall perception in terms of an "overall image quality" (Cadik, et al. 2007) mentioned before in Chapter 7.1.4 Visualisation and Results. Overall the 3 devices show a slight positive average over the benchmark.

6.Immersive Value

IMMERSIVE VALUE Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
SIM2	30	16	0.53	0.81		
OCULUS GO	30	63	2.1	0.71		
HTC VIVE	30	69	2.3	1.39		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	56.16	2	28.08	28.92	2.35E-10	3.10
Within Groups	84.47	87	0.97			
Total	140.62	89				
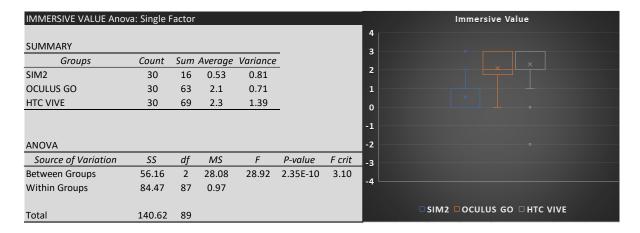
Table 17. Immersive value

Sim2 felt short being slightly better than the benchmark with an average of .53. The headsets scored higher as expected, being virtual reality in nature. Although the p-value rejects the normal sample distribution, it still provides an insight. The p-value will be further discussed in Chapter 9.1.5.

7.User Experience

USER EXPERIENCE Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
SIM2	30	13	0.43	0.46		
OCULUS GO	30	70	2.33	0.44		
HTC VIVE	30	69	2.3	1.46		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	70.96	2	35.48	45.17	3.52E-14	3.10
Within Groups	68.33	87	0.79			
Total	139.29	89				
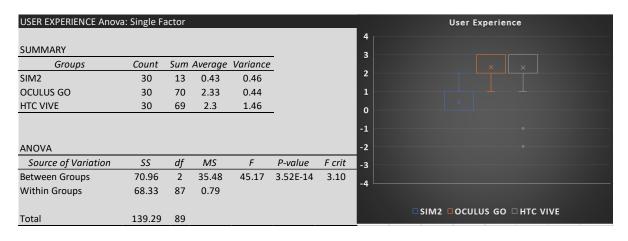
Table 18. User experience

User experience showed to be overall positive against the regular monitor. Headsets scored high again, while HTC Vive received divided opinions from some of the subjects.

8.Value for Design Review

VALUE FOR DESIGN REVIEW Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	19	0.63	0.59		
OCULUS GO	30	68	2.27	0.48		
HTC VIVE	30	65	2.17	1.52		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	50.29	2	25.14	29.17	2.02E-10	3.10
Within Groups	75	87	0.86			
Total	125.29	89				
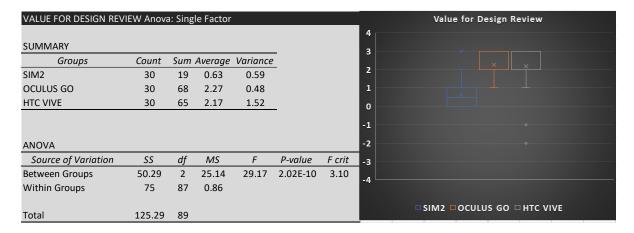
Table 19. Value for design review

This table shows a very similar situation as the User Experience responses, where Sim2 was scored high by a short amount of subjects, Oculus Go scoring consistently high and HTC overall high but falling short due to some negative opinions regarding its value for design review.

9.Appeal/Emotion

APPEAL / EMOTION Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	28	0.93	0.82		
OCULUS GO	30	69	2.3	0.42		
HTC VIVE	30	74	2.47	0.53		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	42.47	2	21.23	35.78	4.58E-12	3.10
Within Groups	51.63	87	0.59			
Total	94.1	89				
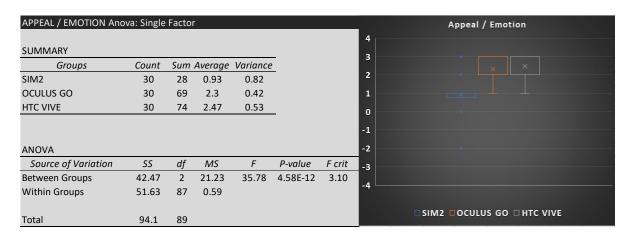
Table 20. Appeal / Emotion

The perception of Sim2 was unexpected, having scattered data throughout the entire rating scale. VR headsets were steadily appealing.

10.Technology benefit on workflow

TECH BENEFIT ON WORKFLOW Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	35	1.17	0.83		
OCULUS GO	30	75	2.5	0.47		
HTC VIVE	30	73	2.43	0.81		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	33.87	2	16.93	24.14	4.58E-09	3.10
Within Groups	61.03	87	0.70			
Total	94.9	89				
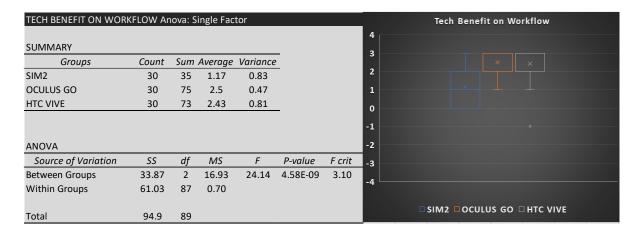
Table 21. Tech benefit on workflow

All of the technologies scored high and by this point a clear trend keeps repeating scoring high for the headsets and positive for the HDR display, where subjects showed a clear positive perception towards these technologies.

11.Engagement Level

ENGAGEMENT LEVEL VS BENCHMARK Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	11	0.37	0.38		
OCULUS GO	30	71	2.37	0.38		
HTC VIVE	30	78	2.6	0.46		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	90.42	2	45.21	111.96	8.70E-25	3.10
Within Groups	35.13	87	0.40			
Total	125.56	89				
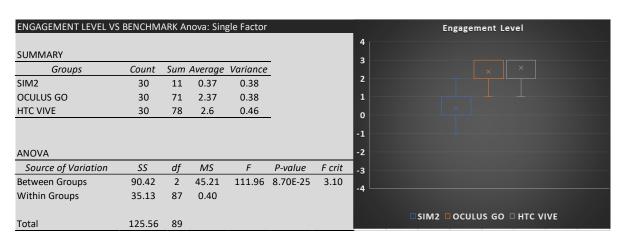
Table 22. Engagement level

Regarding the engagement, same trend kept coming up, where the headsets demonstrate average scores of 2.5, without much variance in response, between 0.38 and 0.46

12.Functional Value

FUNCTIONAL VALUE (DESIGN REVIEW) anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	29	0.97	0.86		
OCULUS GO	30	59	1.97	1.14		
HTC VIVE	30	58	1.93	1.72		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	19.36	2	9.68	7.81	0.00076	3.10
Within Groups	107.8	87	1.24			
Total	127.16	89				
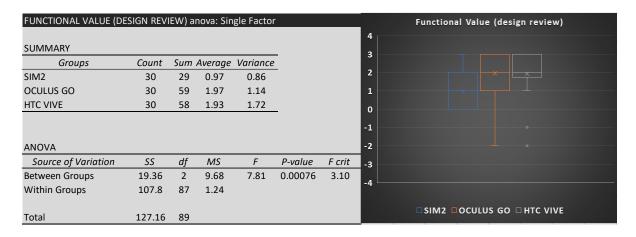
Table 23. Functional value

By functional value, it was intended to reflect how useful these technologies are, but the sample was inconclusive, even though the same trend from previous questions keeps surfacing.

13.Aesthetic communication value

AESTHETIC COMMUNICATION VALUE Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	32	1.07	0.82		
OCULUS GO	30	57	1.9	1.27		
HTC VIVE	30	50	1.67	2.57		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11.09	2	5.54	3.57	0.03	3.10
Within Groups	135.23	87	1.55			
Total	146.32	89				
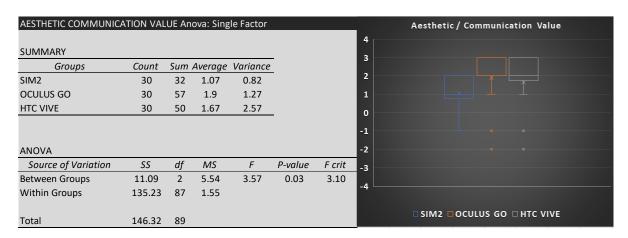
Table 24. Aesthetic and communication value

Apparently, this question as the previous one, shows the same trend, but statistically the sample shows scattered data and fails to provide a true sample. Perhaps in a future study, with a larger participant sample, the data will provide a more uniform array.

8.3.2   Part 2 Questions 14-16

14 If you were/are the decision maker, how likely would you adopt this technology??

	Exposure to Tech						
	Extremely Less	Less	Slightly Less	Same	Slightly More	More	Extremely More
	-3	-2	-1	0	1	2	3
SIM2							
OCULUS GO							
HTC VIVE							
Full Virtual Reality							

Table 25. Technology exposure
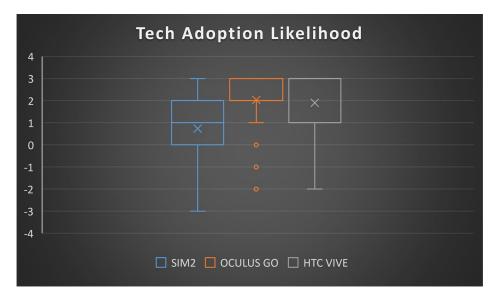
Figure 52. Tech adoption likelihood

15 What is your level of exposure to these technologies?
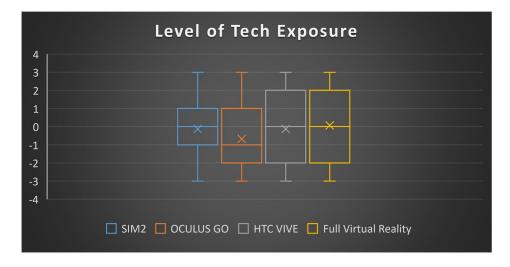
Figure 53. Technology exposure level
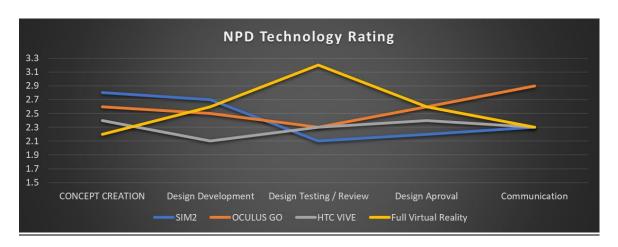
In figure 52 and 53, there is almost a mirror shape between the exposure level against the willingness for using these kinds of technologies. Oculus Go had disperse numbers along the adoption scale, but overall, the participants showed interest of adopting it, although they have not been widely exposed.

16 Rank each visual output according to each product development phase, 4 being the best option and 1 as the worst of them.

NPD Process					
	Concept creation	Design development	Design Testing/Review	Design approval	Design / Eng. Communication
HTC VIVE					
OCULUS GO					
SIM2					
Full Virtual Reality					

Table 26. Technology implementation rating in NPD process

16. **NPD Process Rating**

	CONCEPT CREATION	Design Development	Design Testing / Review	Design Aproval	Communication
SIM2	2.8	2.7	2.1	2.2	2.3
OCULUS GO	2.6	2.5	2.3	2.6	2.9
HTC VIVE	2.4	2.1	2.3	2.4	2.3
Full Virtual Reality	2.2	2.6	3.2	2.6	2.3

Figure 54. NPD visualisation tech average rating

NPD TECHNOLOGY RATING (BY SCORE)

■ SIM2 ■ OCULUS GO ■ HTC VIVE ■ Full Virtual Reality

	Concept Creation Score	Design Development Score	Design Testing/Review Score	Desgin Approval Score	Design/Engineering Communication Score
SIM2	84	81	64	68	70
OCULUS GO	78	75	69	80	89
HTC VIVE	72	65	70	73	71
Full Virtual Reality	66	79	97	79	70
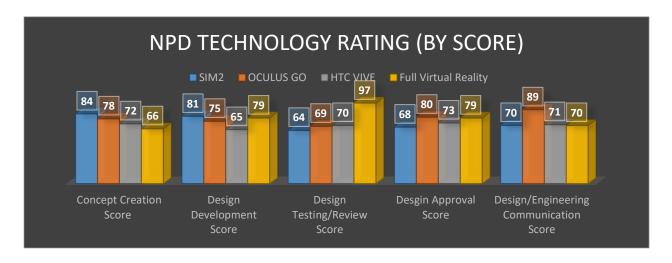
Figure 55. NPD visualisation tech (by score graph)

8.3.3   Part 2   Questions 17-24

These questions were specifically requested by JLR visualisation team. Their objective was to find how change would be embraced and which tendencies in immersive technologies are most common among the engineers to have a better understanding about what different teams within the business are looking for and have a better insight of general needs and the different applications that can be sought after.

Grounded *In Vivo post*-coding technique (Saldaña 2015) was used to classify the responses, according to each code group. E.g. More engaging would belong to the User Experience code group, since it is directly related to how the user perceives the experience. Each coding group was also reviewed and endorsed by two external reviewers, to avoid biased or misinterpreted codes.

These code groups are the following: user experience, design/engineering review, usability, image quality, NPD optimisation, decision making, collaboration, awareness, cost effective/trade off value, limited capability, health & safety, training and reliability.

QUESTION	Code	Answer	Total	SUBJECT
17 Do you think immersive tools would offer more value than the current ones?		Yes	100%	All of the subjects
18 In which way?	User experience	Better sense of space	10	4, 5, 13, 18, 20, 21, 22, 25, 26, 30
		Better interaction	4	17, 18, 19, 30
		Haptic and physical interaction	2	17, 30
		More engaging	1	28
		More realistic	13	2, 4, 5, 6, 8, 13, 18, 20, 21, 25, 26, 28, 31
	Design / Engineering review		2	20, 23
		Better information feedback	6	1, 3, 4, 10, 15, 16
		Early concept review	2	7, 19
		Assessment of requirements	3	29, 30, 31
		Capability/freedom	2	8, 30
	Decision making	Better decision making	4	8, 10, 18, 19
		Appreciation of change	2	12, 29
		Allows quick changes	3	20, 24, 26
	Usability	Easier setup	2	26, 30
		Location flexibility	4	1, 2, 4, 11
	NPD workflow optimisation	Time effective	1	7
		Cost effective	1	14
	(Negative) Individual		1	22

Table 27. Questions 17 and 18
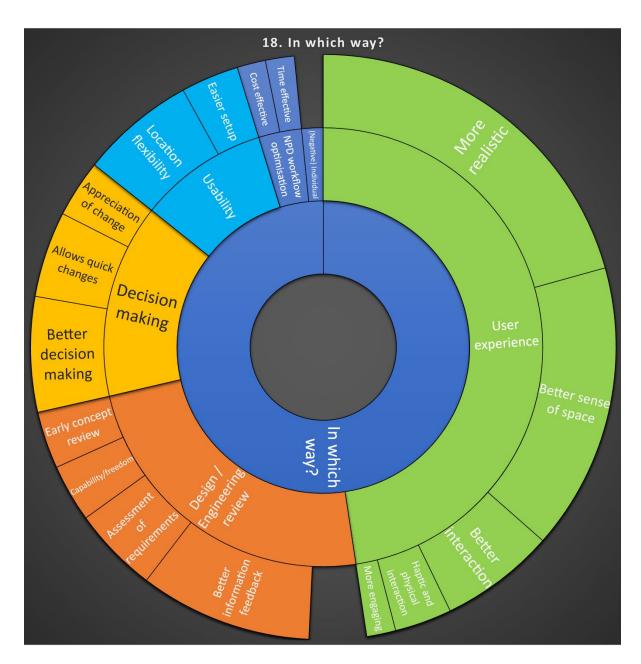
Figure 56. Question 18 answers distribution graph

	QUESTION	Code	Answer	Total	SUBJECT
19	How would you like to see these tools deployed and integrated into JLR's engineering process?	Design / Engineering review		9	2, 3, 5, 11, 13, 17, 18, 19, 20
			Practicality assessment	2	17, 25
			Perceived quality	1	19
			Better information feedback	1	23
			Better assessment in context	1	27
			Assessment of requirements	4	24, 25, 26, 27
			Failure mode identification process	1	20
		Decision making	Decision making	4	15, 20, 23, 24
			Design sign-off	4	1, 2, 3, 16
			At gateways	6	3, 11, 12, 16, 17, 23
			Better for early design stages	2	8, 15
		Usability	Location flexibility	1	6
			Use at desk	4	1, 2, 3, 4
			Use in meeting rooms	1	4
			Accesability	3	22, 26, 30
		Better than CAVE		1	4
		Collaborative / Sharing		1	4
		SIM2 better for demos		1	6
		Awareness		3	23, 28, 31
			Creation of awareness	2	14, 17
			Management engagement	2	14, 30
		NPD workflow optimisation		1	15
			Optimised product development processes	2	20, 25
			Cost effective	1	21
			Less and better physical prototyping	1	21
		User experience		1	14
			Ease of use	1	22

Table 28. Question 19

114
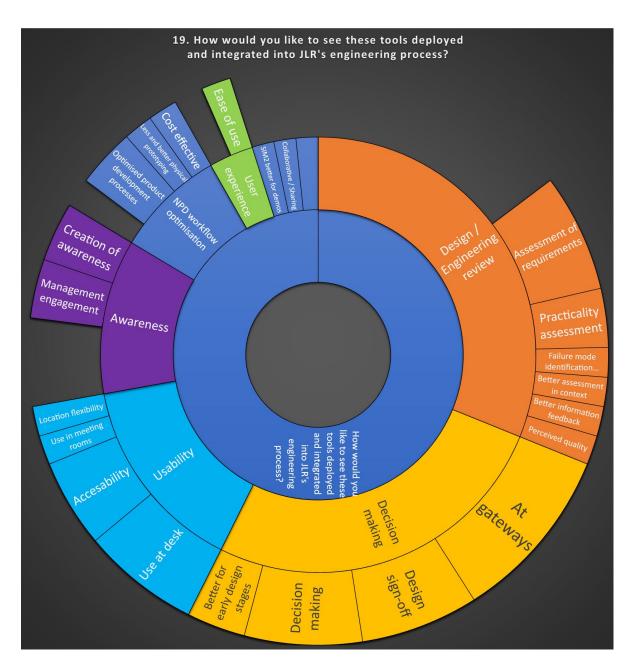
Figure 57. Question 19 answers distribution

The sunburst chart is titled "19. How would you like to see these tools deployed and integrated into JLR's engineering process?"

Center: How would you like to see these tools deployed and integrated into JLR's engineering process?

- Design / Engineering review
  - Assessment of requirements
  - Practicality assessment
    - Failure mode identification…
    - Better assessment in context
    - Better information feedback
    - Perceived quality
- At gateways
  - Decision making
    - Decision making
    - Design sign-off
  - Better for early design stages
- Usability
  - Accesability
    - Location flexibility
    - Use in meeting rooms
    - Use at desk
- Awareness
  - Creation of awareness
  - Management engagement
- NPD workflow optimisation
  - Cost effective
    - Optimised product development processes
    - Less and better physical prototyping
- User experience
  - Ease of use
  - SIM2 better for demos
  - Collaborative / Sharing

	QUESTION	Code	Answer	Total	SUBJECT
20	If you don't think they would be useful, do you think future, enhanced versions would offer this value / benefit? Why?	Cost effective		1	4
		Better decisioin making		2	5, 10
		Design review	HDRI environments test for light and glare, vision tests and FMEA	1	18
		User experience	Haptic and wearable technologies	1	23
			Interaction and capability	1	28
			Adding more interaction elements	1	24
		NPD workflow optimisation	Real-time raytracing	1	24

Table 29. Question 20
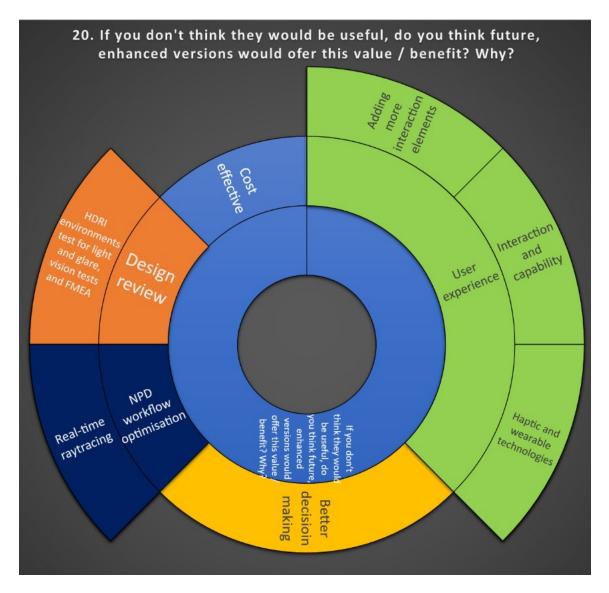
Figure 58. Question 20 answers distribution

	QUESTION	Response	Answer	Total	SUBJECT
21	Do you know people within JLR who could benefit from these technologies?	Yes		96.70%	
			Manufacturing	1	18
			AME/HF	1	17
		No		3.30%	19

Table 30. Question 21

	QUESTION	Response	Answer	Total	SUBJECT
22	Would you recomend the use of HMD's to colleagues?	Yes		100%	All of the subjects
	QUESTION	Response	Answer	Total	SUBJECT
23	Would you be confident using VR hardware in an office environment?	Yes		76.70%	
			As long as it's safe, doesn't distract colleagues	1	7
			In closed office	1	17
		No		23.30%	1, 8, 12, 13
			Not yet, but once learned, yes	1	3
			Loss of awareness of surroundings	1	5
				1	8

Table 31. Questions 22 and 23

	QUESTION	Response	Answer	Total	SUBJECT
24	Would you be confident to use VR equipment and run your own test in this environment?	Yes		96.70%	
			In a safe and clear environment	1	5
			With tracking	1	3
			With training and experience	1	9
			Practicality assessments	1	17
		No		3.30%	13

Table 32. Question 24

8.3.4   Technology Value Open Comments

	Coding	Positive	Total	Subject
HTC VIVE	User experience	Best/better sense of space	5	10, 15, 16, 19, 21
		More realistic	1	9
		User experience	1	19
	Design review	Interior assessment		11
		Exterior assessment		11
		In-context assessment	4	27
		Design review		19
	Decision making	Decision making	1	19
	Usability	Ease of use	1	31
OCULUS GO	Image quality	Better image/resolution	9	7, 14, 15, 16, 17, 20, 21, 27, 28
	Usability	Ease of use	3	3, 18, 28
	Design review	Early design review stages	1	10
		Better information feedback	1	16
		For general visualisation	1	19
SIM 2	Image quality	Better image/resolution	3	3, 5, 7,
	Design review	Design review		10, 26
		Perceived quality	8	10
		Light evaluation		19, 20, 21, 23
		FMEA identification process		27, 31
Full Virtual Experience	User experience	Interaction capability	6	2, 3, 16, 17, 21, 31
		Best/better user experience	6	14, 16, 20, 21, 28, 31
		Best/better sense of space	5	3, 4, 10, 16, 28
		More realistic	1	11
	Design review	Added value for assessment	1	31
		Assessment in context	1	17
		Assessment / Interior	5	5
		Assessment / Performance quality	1	11
		Assessment / Operational quality	1	11
		Design review/early stages	1	10
	Npd Optimisation	NPD value / Decision making		20
		NPD value / Cost effective	3	19
		NPD value / Time efficient		19
	Usability	Haptic/reach	3	10, 13, 16
		Level of freedom	1	3

Table 33. Positive open comments
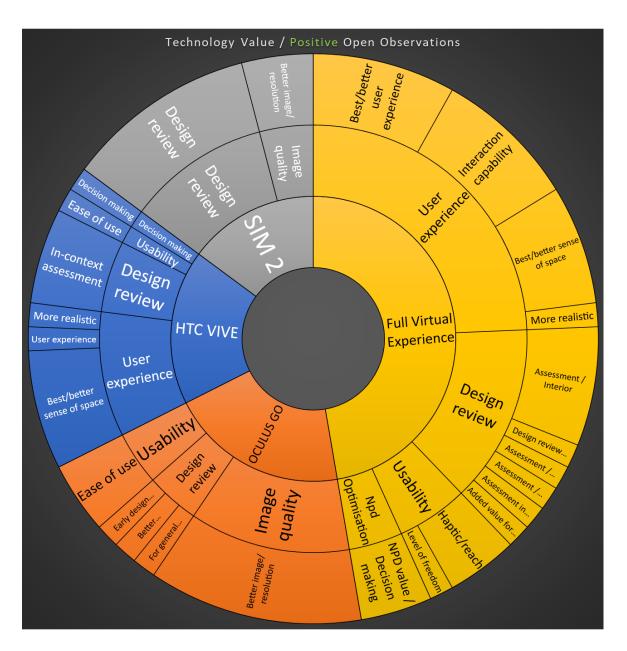
Figure 59. Positive open comments distribution

	Coding	Negative	Total	Subject
HTC VIVE	Image quality	Not clear image	10	7, 8, 14, 15, 16, 20, 23, 26, 27, 28
	Limited capability	Useful, but better full virtual	4	2, 4, 20, 22
	Usability	Limited freedom	1	1
		Usability issues	1	14
	Training	Training concerns	1	18
	Health and Safety	Health and safety concerns	1	31
OCULUS GO	Limited capability	Useful, but better virtual	5	4, 5, 18, 20, 27
	Health and Safety	Health and safety concerns	1	2
	Image quality	Not clear image	1	23
	Training	Training concerns	1	26
SIM 2	Reliability	Too extreme, unreliable	6	9, 13, 17, 18, 27, 28
	Trade-off value	Negative cost/benefit trade-off	2	4, 14
	Limited capability	Limited for assessment	1	2
Full Virtual Experience	Limited capability	Needs improvement	2	22, 23
	Image quality	Not clear image	2	21,27
	Training	Training concerns	1	3

Table 34. Negative comments
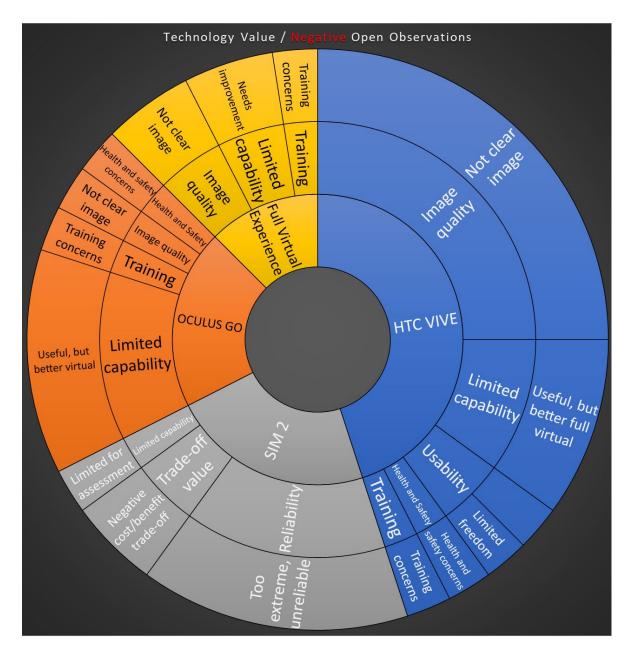
Figure 60. Negative open comments distribution

9   Conclusion and Future Work

9.1   Research Results

The key findings of this research and their implications are discussed focusing on the benefit and value creation from the product development perspective. Overall, based on the evidence previously presented, it is possible to claim there is a substantial TCQ improvement, by implementing the new simulation and visualisation.

9.1.1   Workflow, Data Preparation and Rendering Simulation Time

First, in the data preparation stages (*figure 61),* there is a significant time difference in steps 1 and 5 (*Geometry Conversion* and *Run Simulation / Render)*. In this case, Speos ran 6 simulations simultaneously in 19.8 hours per render vs 3 hours in Vred, considering 6 different rendering scenarios at 4k image size *(Table 35)*.

Software	Geometry Conversion	Part Classification	Material Application	Ambient Sources & Viewpoints	Run Sim / Render
Speos	30	4	2	2	119
Vred	1	2	2	1	3

Table 35. Data preparation timetable (hours)

At the same time, these timings have a very high impact on costs from many different perspectives, ranging from man-hours to other direct and indirect costs. Although the aim of the research does not focus on the financial side of these operations, it is important to acknowledge the impact these improvements may have in the running costs. This topic will be further discussed in Value Proposition, Chapter 9.2.

Vred import tools enable engineers to optimise complex geometries in the most popular formats, saving a huge amount of time. But the greatest improvement at this stage is the raytracing

time, since Speos is not only processing the render, but also making calculations for the optical analysis. This feature is where Speos really excels and is meant to be used for in the first place. The setback is the need of using its interface called "Light Expert" to be able to look at the measurements embedded in the visualisation. Which lead to conclude that Speos is more focused on optical analysis and measurements.
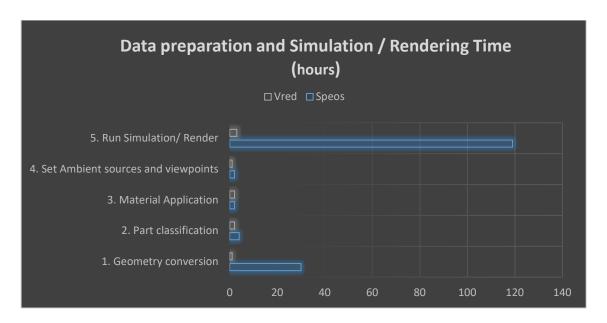
Figure 61. Workflow time in hours

9.1.2   Reflection Study and Visualisation Comparison Results

The reflection study image comparison showed that it is possible to replicate all the lighting conditions and geometry interaction between both software packages. Speos USP resides on the optical analysis, delivering optical and photometric measurements and design tables. In the other hand, Vred USP is about visualisation and design review with the capability of working with photometric parameters, and process images in logarithmic luminance and illuminance, but it is not capable of processing evaluations such as veiling glare index and PJND plots.

Visually, Vred's graphical representations are based on real measurements, photometrically accurate, while material characterisation supports brdf measured files, and material suppliers such as X-Rite and Substance.

Histograms in, *figure 62* provides evidence of similar lightness distribution, indicating the same light conditions in each one of them. The differences are given by the 2 different tone mappings in images 1 and 2, with Physical Camera Image Processing and Reinhard Image Processing respectively.

Figure 62. Visualisation histograms

The second image in *figure 62*, when seen in a 4K monitor provides the sharpest image, with high contrast, which makes it ideal for design review and perceived quality. Visually wise, Vred outputs demonstrated to be the best choice continue using the rest of the project for HDR tone

mapping, GPU denoising, while maintaining lighting and environment conditions accuracy compared with the highest end software package, making images more detailed and clearer in a fraction of the rendering time.

Overall, event though the images show poor use of the grayscale due to the low light conditions and the exposure, and slightly overexposed peaks on the right side of the graphs. Nevertheless, the graphs show consistency between the 3 visualisation outputs, with slight changes on the middle and brighter ranges.

9.1.3   Real environment vs Simulation Verification

At first sight, when comparing both images, it is noticeable that everything related to trigonometrical settings such as sunlight projection towards the car geometry are closely similar. Same shadow cast patterns are present and even reflections appear to follow the same light incidence and behaviour. There are differences in geometry, since the dataset parts were taken from the XE top line model, such as HLDF, interior door panels, instrument cluster, steering wheel and no sun visors, seat belts and roof handles. The physical car matched the virtual scene materials used for the simulation.

In the colorimetry side there are tone and hue level mismatches according to the colour histogram *(figure 63)*, where the virtual scene seems to display more contrast and deeper colours as seen in the middle of the histogram. This is attributed to the camera sensor image capture characteristics compared with Vred's image processing.

Considering the 3 varieties of realism in computer graphics, in the physical realism there is not an accurate point-by-point representation of the spectral irradiance values, nor the materials or the illumination properties of the scene (Ferwerda 2003). But it does work from the functional realism perspective, which in design review is one of the most valuable references.
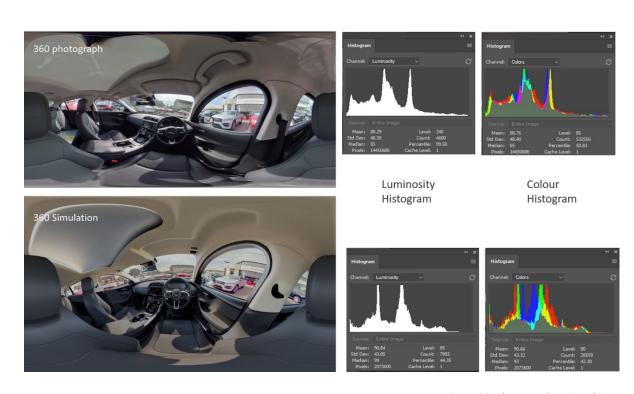
The luminosity histogram *(figure 63)* shows evidence of the close lighting similarity in both images. The photograph histogram shows a higher overall brightness, but still it can be concluded that the simulation closely represents the real environment and lighting conditions. The inverse image processing in this figure also shows the highlights in dark tones and shadow patterns in bright with more clarity. There is room for improvement in the material characterisation, which could represent even closer the material behaviour and details.

9.1.4   Visualisation Trial Part 1 Results

The trial purpose is to determine the value of using immersive visualisation outputs for design review, and at the same time measure the qualitative attributes of the user experience of these technologies. A sample of 30 JLR engineers participated, all related to visualisation roles in some way or another.

In the first section of the Visualisation Trial, a set of 13 semantic differential questions were prepared to map 3 main visualisation aspects:

1. Visual output performance

2. User experience and usability

3. Added value for design review

These 3 ratings are referenced to the benchmark, which is a 4K PC monitor *(table 8)*.

The questions appear in a random order on the answer sheet to avoid biased answers and encourage the subject's reflexion on each one of them. The questions are later clustered in these 3 aspects for clarity *(table 37)*.

Visual output performance	User Experience	Added value for design review
2. Image detail	1. Visual experience	3. Advantage over benchmark
5. Visual performance	4. Usability	6. Immersive value
13. Aesthetic communication value	7. User experience	8. Value for design review
	9. Appeal / Emotion	10. Tech benefit over workflow
	11. Level of engagement	12. Functional Value

Table 36. Trial's part 1 clusters

ONE-Way ANOVA was used to process the semantic differential results, which delivers valuable descriptive statistics *(tables 12-25)*.

In the first group *(figure 64)*, Visual Output, subjects rated Sim2 and Oculus Go as the best performers in image detail, visual performance, but in aesthetic communication there was a near tie between the HMD's, although the P-value in question 13 indicated the null hypothesis is not met or accepted since its *p- value* is minor to 0.05. Additionally, the *F-critical* value is 3.10 which is lower than the *F-value 3.57*, so it is not within the normal distribution, but focusing on the average, the headsets were in general rated high.

IMAGE DETAIL Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	44	1.47	1.09		
OCULUS GO	30	45	1.5	2.05		
HTC VIVE	30	21	0.7	3.18		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.29	2	6.14	2.917	0.059	3.10
Within Groups	183.27	87	2.11			
Total	195.56	89				

VISUAL PERFORMANCE Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	46	1.53	1.50		
OCULUS GO	30	48	1.6	1.70		
HTC VIVE	30	34	1.13	2.26		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.82	2	1.91	1.05	0.35	3.10
Within Groups	158.13	87	1.82			
Total	161.96	89				

AESTHETIC COMMUNICATION VALUE Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
SIM2	30	32	1.07	0.82		
OCULUS GO	30	57	1.9	1.27		
HTC VIVE	30	50	1.67	2.57		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11.09	2	5.54	3.57	0.03	3.10
Within Groups	135.23	87	1.55			
Total	146.32	89				

Figure 64. Visual output group 1

The second group, User Experience, the HMD's rated high over the screens, having a great acceptance among engineers. HTC Vive rated high in questions 1. Visual Experience and 4. Usability, which was surprising, due to the complexity of the setting, using a headset, controllers and remain in the assigned tracking area. In questions 7 and 9 (User Experience and Appeal/Emotion), graphs look very similar, showing a clear high trend among the headsets. In this set all questions all statistical conditions accept the null hypothesis, so they are valid figures.

VISUAL EXPERIENCE Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	60	2	0
OCULUS GO	30	60	2	0.62
HTC VIVE	30	61	2.03	1.55

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.02	2	0.01	0.02	0.98	3.10
Within Groups	62.97	87	0.72			
Total	62.99	89				

USABILITY Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	10	0.33	0.44
OCULUS GO	30	18	0.6	1.77
HTC VIVE	30	21	0.7	3.045

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.16	2	1.08	0.62	0.54	3.10
Within Groups	152.17	87	1.75			
Total	154.32	89				

USER EXPERIENCE Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	13	0.43	0.46
OCULUS GO	30	70	2.33	0.44
HTC VIVE	30	69	2.3	1.46

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	70.96	2	35.48	45.17	3.52E-14	3.10
Within Groups	68.33	87	0.79			
Total	139.29	89				

APPEAL / EMOTION Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	28	0.93	0.82
OCULUS GO	30	69	2.3	0.42
HTC VIVE	30	74	2.47	0.53

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	42.47	2	21.23	35.78	4.58E-12	3.10
Within Groups	51.63	87	0.59			
Total	94.1	89				

ENGAGEMENT LEVEL VS BENCHMARK Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	11	0.37	0.38
OCULUS GO	30	71	2.37	0.38
HTC VIVE	30	78	2.6	0.46

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	90.42	2	45.21	111.96	8.70E-25	3.10
Within Groups	35.13	87	0.40			
Total	125.56	89				

Figure 65. User Experience Group 2

Finally, in group 3, Added Value for Design Review, all questions failed to comply with the statistical conditions of a normal distribution, since all *p-values* were far less than 0.05. But there was a clear high trend on the headsets as it can be seen on *figure 66.*

ADVANTAGE OVER BENCHMARK Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	34	1.13	0.88
OCULUS GO	30	56	1.87	0.74
HTC VIVE	30	52	1.73	2.41

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9.16	2	4.58	3.41	0.038	3.10
Within Groups	116.8	87	1.34			
Total	125.96	89				

Advantage Over Benchmark — SIM2, OCULUS GO, HTC VIVE

IMMERSIVE VALUE Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	16	0.53	0.81
OCULUS GO	30	63	2.1	0.71
HTC VIVE	30	69	2.3	1.39

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	56.16	2	28.08	28.92	2.35E-10	3.10
Within Groups	84.47	87	0.97			
Total	140.62	89				

Immersive Value — SIM2, OCULUS GO, HTC VIVE

VALUE FOR DESIGN REVIEW Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	19	0.63	0.59
OCULUS GO	30	68	2.27	0.48
HTC VIVE	30	65	2.17	1.52

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	50.29	2	25.14	29.17	2.02E-10	3.10
Within Groups	75	87	0.86			
Total	125.29	89				

Value for Design Review — SIM2, OCULUS GO, HTC VIVE

TECH BENEFIT ON WORKFLOW Anova: Single Factor

SUMMARY

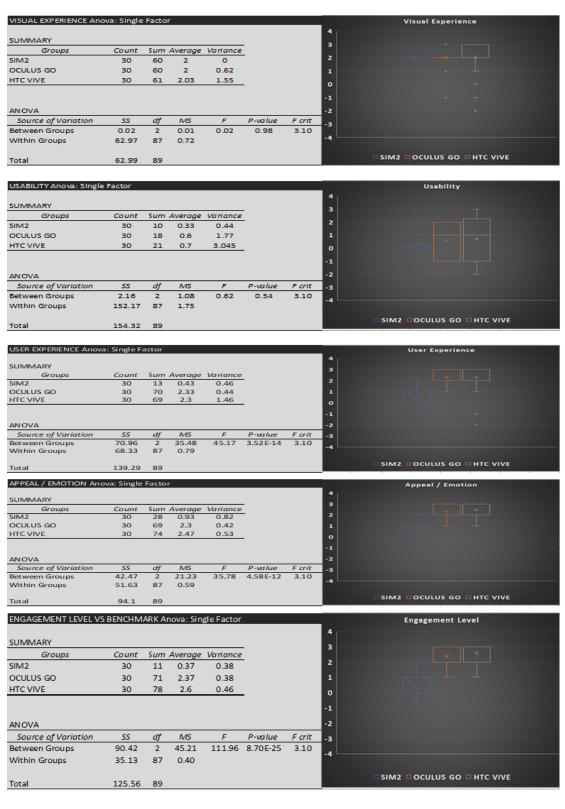| Groups	Count	Sum	Average	Variance
SIM2	30	35	1.17	0.83
OCULUS GO	30	75	2.5	0.47
HTC VIVE	30	73	2.43	0.81

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	33.87	2	16.93	24.14	4.58E-09	3.10
Within Groups	61.03	87	0.70			
Total	94.9	89				

Tech Benefit on Workflow — SIM2, OCULUS GO, HTC VIVE

FUNCTIONAL VALUE (DESIGN REVIEW) anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
SIM2	30	29	0.97	0.86
OCULUS GO	30	59	1.97	1.14
HTC VIVE	30	58	1.93	1.72

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	19.36	2	9.68	7.81	0.00076	3.10
Within Groups	107.8	87	1.24			
Total	127.16	89				

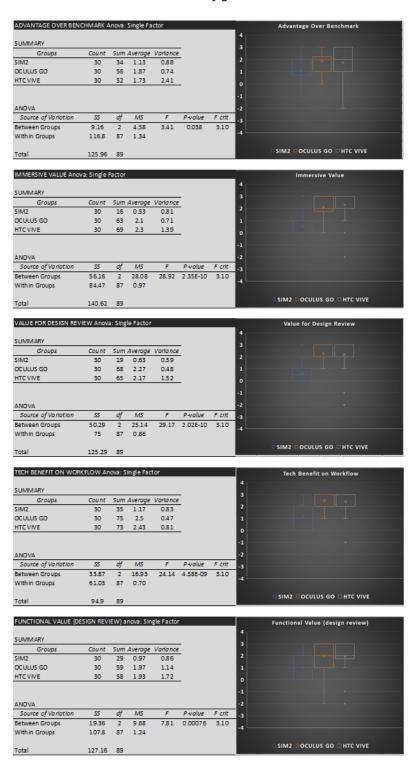Functional Value (design review) — SIM2, OCULUS GO, HTC VIVE

Figure 66. Added Value for Design Review Group 3

It is important to point out that our 30 subject sample is the minimum required to run ANOVA and it is very easy for data to detour from an average trend. Having stated that, the results show a clear high rating of the visual outputs compared to a regular PC monitor, especially when it refers to the virtual reality headsets for an added value design review.

9.1.5 Visualisation Trial Part 2 Questions 14-16 Results

In question 14, the trend showed again a high headset rating as seen in *figure 67*. More importantly, this evidence shows the willingness from the automotive engineers to adopt the visualisation technologies. The *P-value* was .3 falling into a normal distribution.
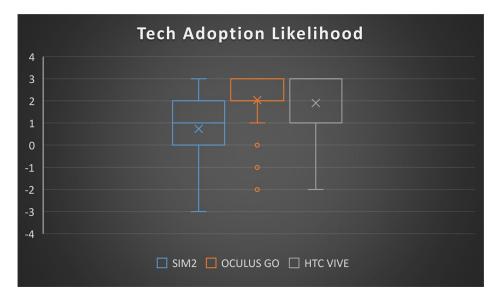
Figure 67. Technology adoption likelihood

Question 15 is just an indicator of the previous acquired exposure level of the HDR monitor, Oculus Go, HTC VIVE and the full virtual experience. The data is quite spread all over the graph with no clear tendency, although in average all engineers have not experienced them at all, as it can be seen in *figure 68*.
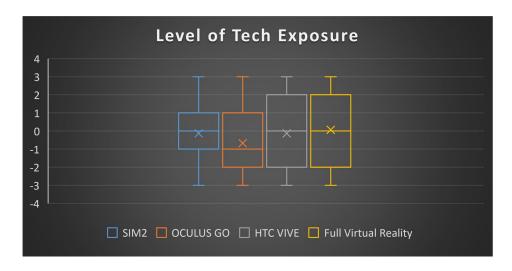
Question 16 shows how the subject would position each technology according to the product development phase: concept creation, design development, design testing/review, design approval and design/engineering communication.

In concept creation SIM2 positioned as the best option while HTC VIVE rated last. Design development rating was tight between Sim2 and HTC VIVE with 81 against 79 respectively. In Design Testing /Review the HTC rated far on the top with 97 and Design/Engineering communication the Oculus Go was the highest with 89.

What is concluded from this NPD technology rating in question 16, is that according to the engineers, there are certain visualisation outputs that would be more useful in different development stage. This is quite an interesting insight, since this is exactly what the research aims to find out. Full Virtual Reality in Design / Testing Review is overwhelmingly high compared with the other technologies.

9.1.6   Visualisation Trial Part 2 Questions 17-24 Results

At this stage, the questionnaire switches to binary answers, yes or no, and reasons why, which are open responses. In order to classify the data, In Vivo coding analytical process for qualitative analysis was developed in collaboration with other two, who coded independently, to later reach a

consensus in order to avoid biased settings and interpretations of the top-level concepts that clustered the subjects' answers. These codes are user experience, design/engineering review, usability, image quality, NPD optimisation, decision making, collaboration, awareness, cost effective/trade off value, limited capability, health & safety, training and reliability.

96.7 % of the engineers agreed that immersive tools would offer more value than the current ones, specially through user experience and in design review as seen *on table 37 and figure 56.* Only one negative comment was captured regarding Sim2 display about being too bright, but this is ultimately an isolated opinion. The latter represents the answers' ratio distribution, making User Experience the most popular code related to the answers. Decision making was the third most popular.

	QUESTION	Code	Answer	Total	SUBJECT
17	Do you think immersive tools would offer more value than the current ones?		Yes	100%	All of the subjects
18	In which way?	User experience	Better sense of space	10	4, 5, 13, 18, 20, 21, 22, 25, 26, 30
			Better interaction	4	17, 18, 19, 30
			Haptic and physical interaction	2	17, 30
			More engaging	1	28
			More realistic	13	2, 4, 5, 6, 8, 13, 18, 20, 21, 25, 26, 28, 31
		Design / Engineering review		2	20, 23
			Better information feedback	6	1, 3, 4, 10, 15, 16
			Early concept review	2	7, 19
			Assessment of requirements	3	29, 30, 31
			Capability/freedom	2	8, 30
		Decision making	Better decision making	4	8, 10, 18, 19
			Appreciation of change	2	12, 29
			Allows quick changes	3	20, 24, 26
		Usability			
			Easier setup	2	26, 30
			Location flexibility	4	1, 2, 4, 11
		NPD workflow optimisation			
			Time effective	1	7
			Cost effective	1	14
		(Negative) Individual		1	22

Table 37. Immersive tools value

When asked how they would like to see these tools integrated into JLR engineering process (question 19), Design Review and Decision Making made the top choices *(table 28 and figure 57),* while usability followed in the third place.

The rest of the questions from 20 to 24, the responses where highly positive in favour of implementing immersive visualisation in the business, and people getting great benefit of it. The only concerns that came up were training and health and safety issues regarding a safe environment to be used, although 96.7% would be confident to use VR to run their own tests.

9.1.7 Technology Value Open Comments

In the final stage of questions, completely open commentaries were registered, dividing them into positive and negative observations. In the positive (table31) the highlights are HTC VIVE convenience for design review and user experience, the image quality of the Oculus Go, the detail of the SIM2 display for light evaluation and the user experience of the Full Virtual Reality walkaround with its interaction capability.

Finally, in *table 34* are shown the negative observations about the visualisation technologies, which in fact were quite few. For instance, the HTC VIVE received most of the critics for its poor image quality. In fact, at the time of the trial, there was already available the HTC VIVE PRO, but for uniformity in the research, the regular version was kept in the trial. The Oculus Go was labelled as useful, but full virtual experience preferred. SIM2 received critics about the brightness intensity, which for some was overwhelming. The full virtual experience received very few concerns.

In conclusion, the trial had a very high acceptance among JLR's engineering staff according to their responses on the Visualisation Trial Results, showing a big interest in trying and using these technologies. The Full Virtual Experience around the Jaguar XE environment was of particular interest for them, especially for the HMI team, where they experience the scale of the interior and reach with the controllers, which had geometry collision and haptic feedback on the steering wheel.

9.2 Value Proposition and New Product Development Facing Emerging Technologies

Along the way of the research development, there are additional recommendations that will actively contribute to the NPD optimisation process, based on the evidence of the simulation process. Some

of these observations refer to how an NPD scheme should nourish the process fluency, and how these characteristics would make more agile and financially sustainable throughout day to day operations.

One of the key issues identified how to face emerging technologies and properly adopt them is the cost-benefit of the tools being used. As it was evidenced in the study, the capabilities of the hardware and software should benefit the process in a whole extent, and a continuous evaluation of resources and benefits should be implemented.

At the beginning of the project Speos was the simulation tool which provided all the images and optical studies, and while looking for visualisation alternatives, a Theia license was purchased to continue working in the same ecosystem. The visualisation was limited to a 360 fixed image with the option of tweaking the light sources intensity. This Theia plug-in alone was £20,000 for an academic license, while Speos was still needed to produce the simulations. So further research was made and then Vred came into the picture.

Vred academic license is free, so it was not long to try it out and discover all the capabilities in a single package. Today an annual license subscription for Vred Pro is £13,500 against £200,000 for Speos.

The point of this argument is that organisations are committed to long term license schemes, where innovation is sometime sacrificed to fulfil complex industrial engineering management and Enterprise Resource Planning (ERP)systems. Today it is not possible to be attached product development tools for long, since technology advances faster than ever. Compatibility and collaboration enablers should be at the centre of the innovation supported by an ISF (Andersen and Andersen 2012).

As it was seen on the workflow, brdf files could not be imported in Vred, since it uses its own pbrdf extension, which supports the idea of compatibility as a best practice among software developers. SIEMENS PLM has adopted JT, Dassault Systèms, Enovia. These 3D formats can facilitate several

process chains ranging from designing to product simulation, validation, manufacturing and downstream life cycle stages.

STEP has gathered a broad support and high stake for the CAD translation, however, due to its technological limitations it is not suitable for viewing purposes.

Functional evaluation uses:

-Viewing of engineering data

-Design in context

-Data exchange between partners in the supply chain

-Packaging and digital mock-up (DMU)

-Documentation and archiving

-Use in the portable PLM document.

In the last decade the JT file format, originally developed by Siemens PLM Software, evolved to a de facto standard for 3D DEV for the automotive and aerospace sector. In 2010, the Global Automotive Advisory Group (GAAG), a forum of international managers of automotive engineering IT, identified the industry endorsement of JT and urged Siemens PLM software to disclose the JT file format definition to the International Standards Organization (ISO) for recognition as an international standard for 3D DEV, deriving into the ISO IS14306:2012.

The benefits of open standards are a reduction in total costs of ownership as well as the autonomy from provider and competition. So, standardisation could only bring benefits to the organisations and the software companies as well, since they will enable people to expand their possibilities, using their products for more purposes. Experts within the company are willing to change, but there is not enough flexibility to do it, besides money or capability. The push of embracing new technologies is clearly in place, but here is a resistance from the management side to not embrace it.

In the other hand collaboration is of the utmost importance, where concurrent engineering, should encourage involvement between different departments or divisions. For some reason,

design/styling and engineering work in different silos, creating inefficiency and process duplicity in some situations.

9.2.1   Challenges for future implementation

Technology development and its implementation has proven to be very important drivers in the industrial transformation and can be significantly positive in NPD (Merimod and Rowe 2012) . Some technologies have never been used before, and may be so disruptive, that user acceptance may be compromised. It may represent a radical change in the way the user engages in a task and may not be well embraced or its potential is simply overlooked (Boland, Lyytinen and Yoo 2007).

This is the reason why it is so important to study the user interaction and how an automotive engineer experiences a new technology intended to improve the workflow.

There is an increasing demand of methods that can properly deal with virtual prototyping and simulation for TCQ optimisation, saving a great amount of resources in the meantime.

The challenge to implement these methodologies reside in the technology readiness levels (TRL) capable of performing complex tasks as real-time rendering and in compatibility with simulation and design review software.

Immersive technologies, particularly VR, is in the process of going mainstream, although they have been around for decades already. The technological improvements and systems integration will gradually converge, but at this point they still need to be further developed and tested. This adaptation process will keep getting even more common in years to come, due to the rapid technology improvement speed. Flexible methodologies that can cope with radical changes and seamlessly integrate into existing structures, are critical in today's industry dynamics. The need of testing and implementing emerging technologies as part of the R&D agenda, is no longer a luxury but a commodity, in order to remain competitive and moreover to become a leader in the field. The use of emerging visualisation technologies is a natural step to follow in the NPD process, not only as a

design aid, but also as a collaborative tool, where the virtual space provides better capabilities in communication and user interface (UI).

9.3 Industry Direction and Future Work

Automotive visualisation will keep up with the Industry 4.0 trends implementing cloud computing as a resource of data in an organisation, which will expand working capabilities such as having access to the information whenever and wherever it is needed, enabling multiple teams to collaborate in a secure environment. Another advantage is the safe keeping of data which is not only stored in the main cloud but also in multiple users' hardware.

As a bold example of innovation and industry 4.0 implementation in the automotive industry there is BMW, which handles 32 million parts and produces 10,000 vehicles per day, looking increasingly to digitalization and flexibility. From autonomous transport systems (ATS) and robots, to augmented reality and paperless systems (Johns 2019).

Today it is possible to virtually attend a design review within a Vred virtual scene by just shares a url. This is a topic for further study and implementation which could bring further benefits through visualisation.

In the same manner real-time raytracing with the use of AI in graphics cards (Kumar Sharma, Khera and Singh 2019) will become a powerhouse throughout the automotive industry, where instant results may become achievable soon, with many industry suppliers such as Autodesk, Ansys and Siemens among others.

The next step in visualisation will be moving from a relatively static to a dynamic simulation, evolving from a static single scene to a comparison between different condition stages, as shown in the PJND plots example of the Optical Simulation, where further interaction with the model will include the 5 senses, where the interaction with the model will feature a wide range of possibilities, including change of conditions.

During the evolution of this research, there were mayor extracurricular opportunities to put in practice the new visualisation methods, in collaboration with different design and engineering teams working in multimillion projects in the transport industry. These companies approached the WMG's Product Evaluation Technologies (PET) department in search for visualisation solutions that could enhance their design review capabilities.

One of these projects is still an on-going effort and is highly confidential, but a couple of examples are worth mentioning, as part of the value proposition and real-case scenario validation of implementing these visualisation methodologies and immersive technologies.

9.3.1   TVS Radeon

TVS is an Indian motorcycle company based in Chennai. Its 2016 their revenue reached U.S. $2.9 billion (TVS Motor Company 2016). In this project the engineering team was in search for a high-end visualisation solution that could realistically represent the aesthetic details for design reviews and shared engineering assets. While working on the Radeon model, one of their high-selling products, the engineers discovered the reach and possibilities of collaboration with the VR environment as a powerful tool to communicate and evaluate their designs.

In this case, working without optical attribute constraints and the lightness of the geometry and part number, led to achieve an almost real-time-rendering environment and photorealistic images, in approximately a 10-hour run from start to finish, even considering there were geometry adjustments being done on their native CAD file and software. Results not only fulfilled TVS engineers' requirements but exceeded their expectations in a very positive way. Working with a highly detailed data and engineering.

9.3.2 Transportation Design International (TDI)

TDI is currently developing a rail guided vehicle as part of Coventry's transportation network called Very Light Rail (VLR). This project has raised $12.2 million from the West Midlands Combined Authority (WMCA) to undertake the R&D and is due to delivery in 2021. It will feature innovative solutions such as electrified power train and self-driving capability.

The new workflow and visualisation methods were implemented throughout various design milestones, especially in close collaboration with the project's senior designer, where geometry, HDRI environments, materials and even presentation sequences were fluently targeted using the system and methods previously acquired.

This case study took off from an early design stage, where the approach was more focused towards the styling and general layout, without fully engineering data, and shaping the engineering intent.

Through VR it was possible to experience the geometry in a real scale, walk through in and out, and interact with many of the parts such as sliding doors. Also, through the design review, the engineering team was able to explain in a high level of detail the mechanical layout and configuration.

Throughout the powerwall and VR outputs used in the design reviews, it was gratifying to watch the positive approval and engagement not only of the design and engineering teams, but also senior management, marketing and media. The efficiency of the process made possible to deliver high quality visualisations and immersive environments across very tight deadlines.

"Thanks for your efforts that made yesterday's event a success. I think the impact of the VR and powerwall presentation helped convince the various partners approve the vehicle design and we can now proceed to the detail design phase and production implementation. I hope our project team can use your facility again in future for design and engineering reviews, as I'm convinced that it's the best way to discuss design problems/solutions for a vehicle of this size and complexity."
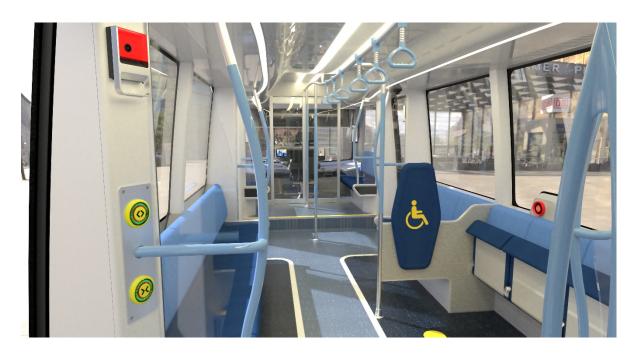
Matthew Hall
Senior Designer, TDI Ltd

For more information on this project follow the link to TDI webpage bellow.

https://www.tdi.uk.com/EN/coventry-very-light-rail-1/ (Transport Design International 2019)

An example of the design review visualisation can be seen at:

https://www.youtube.com/watch?v=L2M3ra4IXqQ (Murguía, Tram Screen 2019)

9.4   Discussion

Through Optical Simulation Analysis, Real Environment Comparison and Visualisation Trial, this study is able to evidence that visualisation and the use of state-of-the-art displays and immersive technologies such as HMD's, play a critical role in achieving better communication of the results and evaluations, transforming this task in a more agile and engaging experience. This translates in a deeper understanding of the design and engineering stages, and proves to be a valuable tool for the NPD process optimisation as shown throughout this study.

In this case, visualisation and technology was the example of how a technology package, well implemented, can outstandingly improve TCQ *(Table 38)*. In the future new technologies will emerge, making the current ones used in this research outdated or even obsolete, but the concept of integrating proven valuable technology into ongoing processes, will provide a better product development performance and a competitive edge.

	Speos	**VRED**
Annual license cost (2018)	£200,000	£13,500
Geometry conversion (complete visible parts)	30 hrs	15 minutes
Simulation / Render	5 days	3 hours
Optical Analysis	Yes	No
Design Tables	Yes	No
HDR output	Yes	Yes
Tone Mapping	No	Yes
360 rendering	Yes	No
VR capability	No	Yes
Remote collaboration	No	Yes
VR interactivity	No	Yes

Table 38. TCQ highlights

For this reason, it becomes critical to implement pilot trials of technology viability, as a common practice in an enterprise environment. The use of immersive technologies is rising to a point where devices are being integrated into a new computing era, while SoC technologies integrate a wide range of components using adaptive circuits, integrated sensors and state of the art power

resources (Bohr 2009), which will develop further to reshape the way in how we interact, collaborate and even learn in a completely new way we have not experienced in the past.

The TRL of VR technologies is in their final steps, where usability and practicality will only improve in the future. At the same moment these lines are being written, new untethered, self-tracking HMDs are commercially available, with more than double of resolution, compared with the headsets used in the research. It is a natural step forward to implement these tools in the automotive NPD at early stages, having provided evidence of its value and approval.

Therefore, this research not only provides a way forward in adopting and implementing immersive technologies, but also provides a solution for process optimisation, improving TCQ, into a highly collaborative structure, where disruptive visualisation trends are positioning themselves as a strong alternative in the product creation process.

In order to identify the complete spectrum of optical design issues there is a need to correlate past, ongoing and prospected projects within the PCDS. After analysing the SOF modes, traceability and information management is of the utmost importance to avoid process duplicity and populate the design rule list of best practices and standards, since simulation depends on the data quality and quantity to accurately replicate reliable scenarios.

As an example of the importance of technology early adoption and as an important lesson of analysing each step of the simulation process, which is a deterministic method, it can be predicted that visualisation will benefit from IoT, AI and big data by implementing them into a virtual environment (Martinez, et al. 2018), since the more quality data that is put into a dataset, the better-quality output obtained, as seen throughout in the data preparation of this study.

As an assumption, after the developing the study in *Chapter 8 Simulation VS Real Environment Comparison,* it can be suggested that in the future the 360 camera or even a smartphone, can easily transfer each photograph setting to the simulation software, and also include data such as location or weather. This data can populate a database of inputs and outputs, which will

be further analysed by algorithms (Li, et al. 2019) with (n) number of combinations, to finally produce a robust visualisation or VR environment.

This assumption may seem to fall out of place in a visualisation research like this, but there is evidence to sustain that the technological applications used in these studies are heading in that direction. Nevertheless, the point is that early adoption provides a competitive edge and is an innovation booster (Rogers 1983). In the other hand, provide designers and engineers with better tools to improve their results.

With the growing trend of managing the organisation assets through a digital twin, visualisation should be a priority to enhance productivity and user experience through the emerging virtual platforms.

9.5 Conclusion

The evidence shown in this research places visualisation as a strong NPD optimisation tool and value creation enabler. From creating more efficient workflows, to user experience optimisation, new solutions are provided to enable better decision making, and significantly improve TCQ.

The alternative hardware and software tested throughout this research is an added value source to the NPD process, especially in the early design stages, as it has been assessed in the workflow analysis.

The proposed visualisation software can reproduce most of the conditions of a real-life scenario as seen throughout Chapters 6 and 7, with outstanding accuracy, delivering a high level of photorealism and detail, which reassures the certainty of the simulation, although there is still long way to go, to get an exact representation. In the other hand, Speos is still the leading automotive optical analysis software, needed for optical validation in final gateways and design sign-off. In September 9th of 2019, Ansys and Autodesk announced a collaboration between Speos and Vred (Ansys 2019), which also validates the findings of this research, where the ideal scenario of Speos optical analysis is combined with the superior visualisation output of Vred.

This announcement also means software developers are heading together towards compatibility and standardisation, which creates a very positive range of possibilities to improve the product lifecycle management, from the product creation, to the consumer.

This research also provides a feasible example of technology adoption which can bring huge improvements to the NPD process. As seen in other case studies, this methodology and workflow can be transferred to other transportation industries, delivering the same value proposition of this study.

Considering the 3 varieties of realism in computer graphics, in the physical realism there is not an accurate point-by-point representation of the spectral irradiance values, nor the materials or the illumination properties of the scene (Ferwerda 2003). But it does work from the functional realism perspective, which in design review is one of the most valuable references.

Collaboration through the design review capabilities can bring together design and engineering teams, while improving certainty in decision-making. Moreover, optimisation through visualisation will continue to grow in relevance with the growing necessity of a digital twin implementation to be integrated into the Industry 4.0 trend.

The integration of these virtual capabilities within the product development stages, is crucial to reduce TCQ and improve the value stream within the design and engineering operations structure. Simulation and visualisation relevance in today's digital era, demands updated technology management solutions, that promotes innovation implementation as a high priority, in the entire product development scheme. This study provides an example from a simulation and visualisation approach to deliver that.

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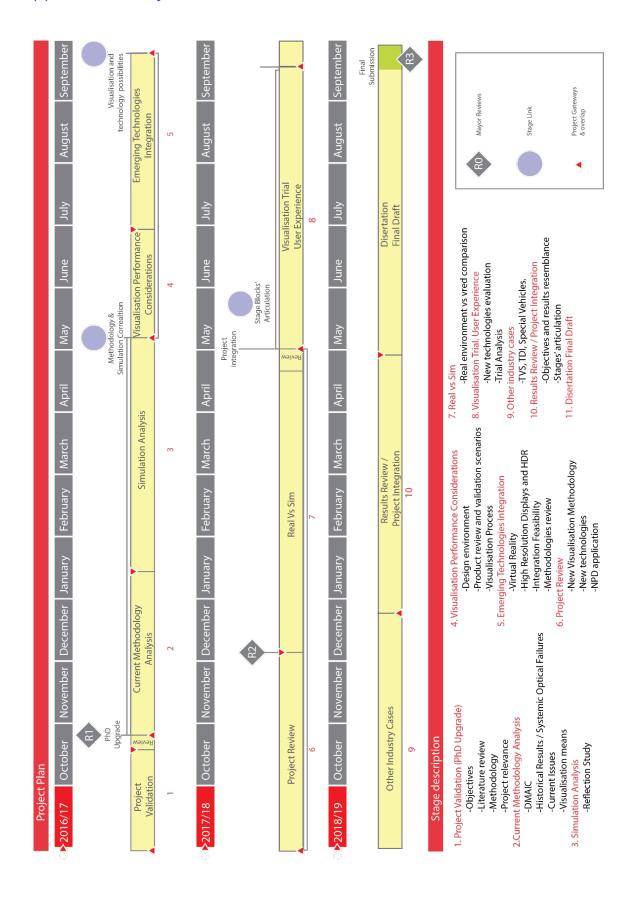
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Appendices

Appendix A. Project Plan

Appendix B. WMG Pilot Trial Protocol

Introduction

Automotive lighting simulation software packages have significantly evolved in the last decades to become an outstanding engineering tool within the product development phase, providing timely and informed decisions from early design stages and having a deep impact in the final configuration and performance.

This trial is based on VRED, a state-of-the-art application used in lighting simulation, design review and perceived quality, where a Jaguar XE 3-D model is featured in 5 different environment scenarios and light conditions.

Objectives

Evaluate how experienced JLR engineers actively involved in product development perceive visualisation outputs. Translate qualitative data such as perceived visualisation quality or user experience into data which enable a value proposition mapping of each technology, which will be subsequently compared against visualisation process improvement in a further study.

Methodology
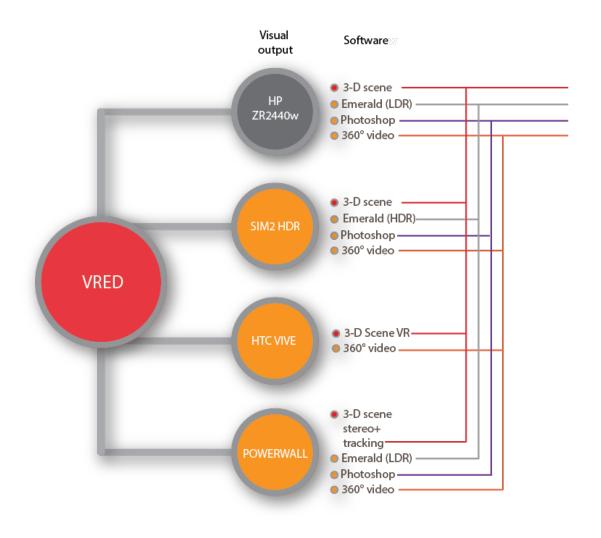
VRED visualisations are presented through four different display outputs, taking a Full HD PC monitor (HP AR2440w) as a benchmark:

Specification	HP ZR2440w	SIM2 HDR47	HTC VIVE	POWERWALL 4K
	Benchmark			
Type	24.1" LED backlit LCD	48" LCD TFT + LED BLU + HDR	VR HMD dual AMOLED 3.6". Field of view 110 degrees	Dual JVC D-ILA Ultra High Resolution
Resolution	Full HD 1920 x 1200	Full HD 1920 x 1080	1080 x 1200 per eye (2160 x 1200 combined)	4096 x 2400
ANSI Contrast Ratio	1000:1	15,000:1	Infinite	300:1
ON/OFF Contrast Ratio	2,000,000:1	4,000,000:1		10,000:1
Colour Temperature	5000K, 6500K, 9300K	5000K, 6500K, 7500K		5800K (typical)
Brightness	350 nits cd/m²	2300 nits cd/m²		3500 lm – 1000 nits cd/m²
Colour Depth	16.7 million colours	68 billion colours		

Each display output will be assessed referring to a PC monitor as a benchmark, then a **comparison between displays** will be made, using a scale where:

0 NEITHER (not better or worse)

1 SLIGHTLY BETTER

2 QUITE BETTER

3 EXTREMELY BETTER

-1 SLIGHTLY WORSE

-2 QUITE WORSE

-3 EXTREMELY WORSE

The goal is to map each experience and technology value proposition through the participants' experience against a regular PC monitor, which is the visual tool used in a daily basis. Participants will also rate each experience and how valuable it is to the new product development process.

Questionnaire

Dept._____Role_____

Age_____ Gender (Male)(Female)

Visual outputs vs benchmark

1 How better or worse is the visual experience?

Visual Experience							
	-3	-2	-1	0	1	2	3
SIM2							
HTC VIVE							
POWERWALL							

2 How would you rate the visual detail?

Visual Detail							
	-3	-2	-1	0	1	2	3
POWERWALL							
SIM2							
HTC VIVE							

3 How strong would you say the advantage is against the benchmark?

Advantage Over Benchmark							
	-3	-2	-1	0	1	2	3
HTC VIVE							
POWERWALL							
SIM2							

4 Usability vs Benchmark?

Usability							
	-3	-2	-1	0	1	2	3
SIM2							
POWERWALL							
HTC VIVE							

5 How better or worse the overall performance is?

Performance							
	-3	-2	-1	0	1	2	3
POWERWALL							
HTC VIVE							
SIM2							

6 How useful is the immersive value proposition?

Immersive Value							
	-3	-2	-1	0	1	2	3
HTC VIVE							
SIM2							
POWERWALL							

7 How would you rate each 360 experience on each display?

360 User Experience						
	-3	-2	-1	0	1	2	3
POWERWALL							
HTC VIVE							
SIM2							

8 How useful do you find 360 visualisations for design review?

360 Value For Design Review						
	-3	-2	-1	0	1	2	3
HTC VIVE							
SIM2							
POWERWALL							

9 How appealing to use is it compared with the benchmark?

Appeal / Emotion						
	-3	-2	-1	0	1	2	3
SIM2							
HTC VIVE							
POWERWALL							

10 How better do you think a design review can be done with 360 on each display?

360 for design review						
	-3	-2	-1	0	1	2	3
SIM2							
POWERWALL							
HTC VIVE							

11 What is the level of exposure you have had to each technology on your job?

Exposure To Tech						
	-3	-2	-1	0	1	2	3
SIM2							
POWERWALL							
HTC VIVE							

12 How beneficial would this tech be for visual aids and workflow in an engineering/design environment?

Tech Benefit On Workflow							
	-3	-2	-1	0	1	2	3
HTC VIVE							
SIM2							
POWERWALL							

13 How engaged/involved did you feel with each output compared with the benchmark?

Engagement Level vs Benchmark							
	-3	-2	-1	0	1	2	3
HTC VIVE							
POWERWALL							
SIM2							

14 How would you rate the functional value vs benchamark?

Functional Value							
	-3	-2	-1	0	1	2	3
HTC VIVE							
POWERWALL							
SIM2							
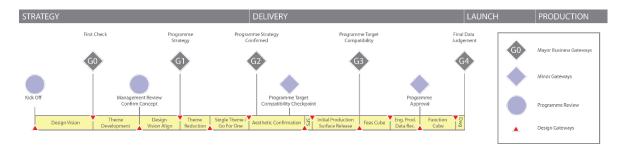
15 As aesthetic value, how would you rate each output for communicating?

Aesthetic Value For Communication							
	-3	-2	-1	0	1	2	3
HTC VIVE							
POWERWALL							
SIM2							

15 If you were/are the decision maker, how likely would you adopt this technology?

Tech Adoption Likelihood							
	-3	-2	-1	0	1	2	3
SIM2							
HTC VIVE							
POWERWALL							

16 Where would you place these visual outputs in the PCDS ? cancel and rewrite.

	NPD Process				
	Concept creation	Design development	Design Testing/Review	Design approval	Design / eng. Communication
HTC VIVE					
POWERWALL					
SIM2					

17 Comments or observations concerning Technology Value Proposition for NPD process

Open Comment Tech Value	
HTC VIVE	
POWERWALL	
SIM2	

Appendix C. BSREC Full Trial Protocol Approval

WARWICK
THE UNIVERSITY OF WARWICK

<u>PRIVATE</u>
Mr Fernando Murguia
WMG
University of Warwick
Coventry
CV4 7AL

29 June 2018

Dear Mr Murguia

Study Title and BSREC Reference: *Visualising Lighting simulations for Automotive Design Evaluations Using Emerging Technologies* REGO-2018-2190

Thank you for submitting the revisions to the above-named study to the University of Warwick's Biomedical and Scientific Research Ethics Sub-Committee for approval.

I am pleased to confirm that approval is granted.

In undertaking your study, you are required to comply with the University of Warwick's *Research Data Management Policy*, details of which may be found on the Research and Impact Services' webpages, under "Codes of Practice & Policies" » "Research Code of Practice" » "Data & Records" » "Research Data Management Policy", at:
http://www2.warwick.ac.uk/services/ris/research_integrity/code_of_practice_and_policies/research_code_of_practice/datacollection_retention/research_data_mgt_policy

You are also required to comply with the University of Warwick's *Information Classification and Handling Procedure*, details of which may be found on the University's Governance webpages, under "Governance" » "Information Security" » "Information Classification and Handling Procedure", at:
http://www2.warwick.ac.uk/services/gov/informationsecurity/handling.
Investigators should familiarise themselves with the classifications of information defined therein, and the requirements for the storage and transportation of information within the different classifications:

    Information Classifications:
    http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/classifications
    Handling Electronic Information:
    http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/electronic/
    Handling Paper or other media
    http://www2.warwick.ac.uk/services/gov/informationsecurity/handling/paper/.

Please also be aware that BSREC grants ethical approval for studies. **The seeking and obtaining of _all_ other necessary approvals is the responsibility of the investigator.**

These other approvals may include, but are not limited to:

www.warwick.ac.uk

1. Any necessary agreements, approvals, or permissions required in order to comply with the University of Warwick's Financial Regulations and Procedures.
2. Any necessary approval or permission required in order to comply with the University of Warwick's Quality Management System and Standard Operating Procedures for the governance, acquisition, storage, use, and disposal of human samples for research.
3. All relevant University, Faculty, and Divisional/Departmental approvals, if an employee or student of the University of Warwick.
4. Approval from the applicant's academic supervisor and course/module leader (as appropriate), if a student of the University of Warwick.
5. NHS Trust R&D Management Approval, for research studies undertaken in NHS Trusts.
6. NHS Trust Clinical Audit Approval, for clinical audit studies undertaken in NHS Trusts.
7. Approval from Departmental or Divisional Heads, as required under local procedures, within Health and Social Care organisations hosting the study.
8. Local ethical approval for studies undertaken overseas, or in other HE institutions in the UK.
9. Approval from Heads (or delegates thereof) of UK Medical Schools, for studies involving medical students as participants.
10. Permission from Warwick Medical School to access medical students or medical student data for research or evaluation purposes.
11. NHS Trust Caldicott Guardian Approval, for studies where identifiable data is being transferred outside of the direct clinical care team. Individual NHS Trust procedures vary in their implementation of Caldicott guidance, and local guidance must be sought.
12. Any other approval required by the institution hosting the study, or by the applicant's employer.

There is no requirement to supply documentary evidence of any of the above to BSREC, but applicants should hold such evidence in their Study Master File for University of Warwick auditing and monitoring purposes. You may be required to supply evidence of any necessary approvals to other University functions, e.g. The Finance Office, Research & Impact Services (RIS), or your Department/School.

May I take this opportunity to wish you success with your study, and to remind you that any Substantial Amendments to your study require approval from BSREC before they may be implemented.

Yours sincerely

pp.

Dr David Ellard
Chair
Biomedical and Scientific
Research Ethics Sub-Committee

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ris/research_integrity/researchethics
committees/biomed

Appendix D. Trial Protocol and Ethical Considerations

Project title: <u>Visualising Lighting Simulations for Automotive Design Evaluations Using Emerging Technologies.</u>

Trial: Simulation/Visualisation outputs trial

Lay summary

Today's automotive New Product Development processes utilise a variety of simulation techniques to deliver the best possible products as efficiently as possible. Simulation enables informed decisions to be made early in the design process, long before physical prototypes are available for testing, but this is only possible if the results of the simulation can be interpreted by those responsible for the product's development. Whilst the outcomes of crash simulations and dimensional variation can be visualised relatively easily, the effects of lighting on the various visual aspects of a vehicle interior (display readability, reflections, colour reproduction, interior lighting effects etc.) can be difficult to communicate.

As new in-vehicle technologies are created and developed into products, consideration must be given to how the customer will interact with the technologies, and what influence ambient light will have on the interaction process. Being able to simulate, predict, and understand the visual interaction process between the vehicle interior, the ambient light, and the customer, is critical for optimising the design.

This project utilises new and emerging technologies (both in terms of hardware and software) to develop new methods for communicating effectively the outputs from visual simulations of vehicle interiors under different lighting conditions. Key objectives include the development of methods for visualising and communicating the simulated effects of lighting on vehicle interior design and new in-vehicle technologies. The selection of appropriate hardware and software tools to optimise the communication of vehicle interior simulations, and the determination of where these tools can best be utilised to deliver the most efficient technology/product development process possible. The research will complement the ongoing developments of the JLR Virtual Innovation Centre at Gaydon, the visualisation capabilities proposed for the forthcoming National Automotive Innovation Centre

at the University of Warwick, and a current Doctorate project investigating the effect of ambient light on the readability of in-vehicle displays and the best workflow scheme that results from it.

Background

JLR, being in the premium automotive segment, is highly focused on delivering "zero-defect" high quality products to go beyond the customer's requirements. Therefore, Perceived Quality (PQ) is a high priority topic that goes beyond functionality and engineering itself. To fulfil this objective, from early product development stages, these customer requirements are translated into technical specifications (Stylidis, Rossi, et al. 2016) with the highest accuracy, to reduce to a minimum, failures in prototype iterations and prepare a smooth transition to the manufacturing phase. However, the need of achieving high accuracy levels in many development stages, has led to implement perceived quality to an engineering level, which no longer deals with marketing studies, consumer surveys and applied psychology (Stylidis, Rossi, et al. 2016). In this sense, further from socio-cultural segmentation (Petitot, et al. 2009), quality needs to be measured to later be applied into high technical quality.

JLR optical inter-attribute is currently focused on HMI performance analysis, but the visualisation reach may get to areas such as geometrical variation and impact on product experience (Forslund, Karlsson and Söderberg, Impacts of Geometrical Manufactruring Quality on the Visual Product Experience 2013), where the customer expectations and needs are a main concern which need to be accurately identified and targeted from the engineering requirement process (Stylidis, Rossi, et al. 2016), and can be greatly enhanced by other disciplines such as analytical product design where marketing, policy and standard environments are also considered along with the engineering specification and requirements to finally build a design decision model framework (Frischknecht, et al. 2009).

Objectives

a) Develop methods for visualising and communicating the simulated effects of lighting on vehicle interior design and new in-vehicle technologies while selecting the appropriate hardware and software tools to optimise the communication of vehicle interior simulations, and the determination of where these tools can best be utilised to deliver the most efficient technology/product development process possible, establishing a clear assessment of how seamlessly the integration of emerging visualisation technologies such as VR and AR can be executed into NPD methodologies.

More specifically, this integration will be focused on lighting simulations and its visualisation at different levels in order to establish the level of certainty for decision makers and designers to have the best confidence and informed choices in an early stage of the whole product engineering. This should be accomplished by analysing the current processes (product lifecycle, NPD, etc.) in comparison with new technologies applied for process optimisation.

b) Achieve a high level of lighting accuracy comparable with reality and how to communicate it in the most efficient way.

c) To establish a methodology to mitigate the Systemic Optical Failure (SOF) modes such as *veiling glare* and enable the flexibility to be adapted to new immersive technologies and its implementation, in order to improve the decision making and design evaluation processes within JLR's PCDS (Product Creation and Delivery System) scheme.

d) To develop a new technology adoption procedure within the product development scheme, since technology escalates exponentially through time with new hardware and software. To keep up with more efficient tools, and continuously optimise time to market, quality and cost, through the implementation of a versatile workflow structure.

e) By testing different visualisation outputs, the user will provide feedback of the visualisation experience with the latest visualisation tools. The value proposition of each technology will be confronted with the use of resources through the process and most efficient workflow implementation, to determine an integral value proposition of these technologies.

Design Methodology

This is a qualitative prospective study where the visualisation outputs are being tested through the observer's perception and experience, using 4 different visual outputs and experiences. The subject will then respond a questionnaire where he/she will rate the visual outputs and give final comments and observations.

Part 1

VRED visualisations are presented through four different display outputs, taking a 4K PC monitor (Samsung UHD UE850) as a benchmark:

	Samsung UE850	SIM2 HDR47	HTC VIVE	Oculus Go
Specification	 Benchmark			
Type	28" LED backlit LCD	48" LCD TFT + LED BLU + HDR	VR HMD dual AMOLED 3.6". Field of view 110 degrees	Dual JVC D-ILA Ultra High Resolution
Resolution	Full HD 3840 x 2160	Full HD 1920 x 1080	1080 x 1200 per eye (2160 x 1200 combined)	1280 x 1440 per eye 2560 x 1440
ANSI Contrast Ratio	1000:1	15,000:1		
ON/OFF Contrast Ratio	2,000,000:1	4,000,000:1		
Colour Temperature	5000K, 6500K, 9300K	5000K, 6500K, 7500K		
Brightness	370 nits cd/m²	2300 nits cd/m²		
Colour Depth	1.07 billion colours	68 billion colours		

Part 2
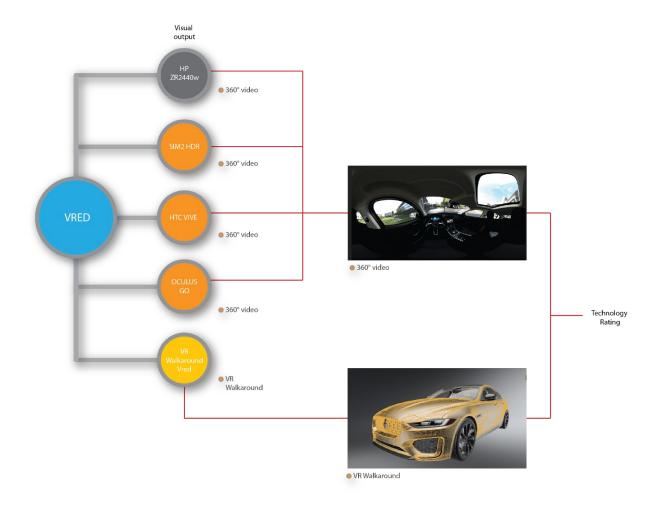
A full VR experience walk around with a Jaguar XE virtual model will be presented, considering its use for a multiple user design review. This demo will be ran through VRED and HTC Vive.

Each display output will be assessed referring to a PC monitor as a benchmark, then a **comparison between displays** will be made, using a scale where:

0 SAME (not better or worse)

1 SLIGHTLY BETTER

2 QUITE BETTER

3 EXTREMELY BETTER

-1 SLIGHTLY WORSE

-2 QUITE WORSE

-3 EXTREMELY WORSE

The main objective is to map each experience and perceived technology value proposition through the participants against a regular PC monitor, which is the visual tool used in a daily basis. Participants will rate each experience and how valuable it is for the new product development process using the scale above in the questionnaire provided in appendix E. By the end of the trial, the different output's evaluation will be mapped against each other and will be put against the resources needed for using each one of them **in a further project's phase** (not part of the current trial results).

The participants' sample is expected to be between 15 to 30 participants, considering the subjects that can be currently reached. At the same time, these participants will be divided into 2 groups:

1) Experienced JLR engineers

2) Post-graduate researchers

In group 1, there are members of the OCAE and engineers from the Virtual Innovation Centre (VIC), who have collaborated with the researcher throughout the PhD. Some of them will be contacted via e-mail and other contacts will be provided by JLR's team leaders. Group 2 will be contacted via email to known people within WMG. Then the results will be compared between them to correlate the experienced group acceptance against the least experienced

one and check if there are any variations among both. The trial will be executed at both JLR and WMG facilities if necessary, depending on the sample response and availability.

The invitation is completely open for people who want to get to participate in this trials and no obligation in taking part is expected. Other members of the research group have completely different research lines, so no biased answers are susceptible of taking place within the subjects, which could alter the trial results.

No subjects with special considerations such as pregnant women, motions sickness or even colour blindness are expected to participate in the trials. It will be asked if the participant has any special condition, and if so, he or she will be asked **not** to take part in the trial to avoid any risk.

Visualisations take 2 mintues 40 seconds, (40 seconds per display), where a video with different lighting conditions of a virtual Jaguar XE will be displayed as the example below.

1. The last section of comments and observations will be analysed through In Vivo coding analytical process for qualitative analysis and use of constant comparative technique to spot similarities and differences, coherence and incoherence within categories, relevance and alternative conceivable categories (Miles 1994), which will be used as a complement for the rating section (see appendix E).

Ethical Considerations

Subjects will be briefed completely at the beginning of the trial, making clear the right to withdraw at any moment if desired, also explaining strict ethical and legal practice and all information about him/her will be handled in confidence. Each participant will be shown a "Participant Information Sheet", where he/she could find all the information about the study, the

trial procedure in detail, possible discomforts, study benefits, confidentiality and data security and

how to contact an authority if there may be any complaint.

Informed consent and confidentiality: Previously to starting the trial, a consent form will be signed by participants from both of the groups previously mentioned. After reading the information sheet (appendix 1), each participant should sign a consent form (appendix 2) where only age will be asked for taking in consideration age visual acuity range. No name, gender or occupation will be part of the data. Personal data and identity will be kept in complete anonymity and will not be used in the findings. Participation in this study is entirely voluntary. Refusal to participate will not affect the subject in any way.
The subject may nevertheless withdraw from the study at any time without affecting him/her in any way and no further contact from the staff will be made.

Data Security: The results will be stored in the researcher's personal cloud storage (Microsoft One

Drive), where only he has access and backed up in encrypted hard drives and kept at the researcher's

home. Physical documents will be stored and locked in a drawer at the researcher's home for ten

years. All in accordance with the General Data Protection regulation (GDPR) and Data Protection Act

2018.

Right of Withdrawal: Participants have the right of withdrawal at any time during the trial, which is

stated on their consent form (Appendix 2). After any publication, if it is the case, the right of

withdrawal would have expired.

Sensitive Disclosures: No sensitive data will be disclosed duet to the non-disclosure agreement with

JLR's collaboration. Only the results' figures will be used to illustrate the results.

Benefits and Risks: The subject will be able to test novel technologies that are currently shaping future visual experiences. Some of them are thought to go mainstream in the next years such as VR. This study will help to trace the benefits of implementing these technologies in a daily workflow and predict usability issues and adaptability.

While using the HMD, some discomfort may be experienced for first time users, such as dizziness, loss of equilibrium or the so called virtual reality sickness. Most of VR users adapt very quickly to the HMD sensation, but the user should suspend the trial at any moment he or she feel any kind of discomfort. (Appendix 1)

Financing and Dissemination

This PhD research (Visualising Lighting Simulations for Automotive Design Evaluations Using Emerging Technologies) is financed by the EPSRC. The information is subject to a non-disclosure agreement between both parts. This trial will need no further financing for its execution and no

incentives will be offered to the participants. The project's dissemination will publish some of the results in scientific journals, where specific information will be subject to the sponsor's review.

Appendix E. Part 1 Questions Information Sheet

Part 1 Questions Info Sheet	Explanation
Visual experience	Subject's visual perception towards a determined visual output over benchmark
Image detail	Refers to resolution and image sharpness over benchmark
Advantage over benchmark	How better or worse the output is for design review over benchmark
Usability	Ease of use and practicality over benchmark
Visual performance	Refers to brightness, contrast, and colour depth benefit for design review over benchmark
Immersive value	Level of immersive benefit for design review over benchmark
User experience	Overall usability
Value for design review	Benefit for design review over benchmark
Appeal / Emotion	Sense of realism and immersive impact on the senses over benchmark
Tech. benefit on workflow	How beneficial the technology is for displaying CAD, designs and simulations
Engagement level	How enjoyable the output is over benchmark
Functional value	How useful it is over benchmark
Aesthetic communication value	How visually appealing (nice) it is for design review over benchmark

Appendix F. Visualisation Trial Questionnaire

No. _____   **Technology Rating Questionnaire**

User Profile
1. JLR Role _____
2. Engineering purpose for visualisation technology _____
3. Are you aware of the current immersive visualisation capabilities available for engineering use within JLR? Yes_____   No_____
4. Have you ever used JLR CAVE? Yes_____   No_____
5. If Yes, for what purposes? _____

Part 1
Visual outputs VS benchmark (pc monitor)   Please mark the space with a ✔ where you believe the technology stands against the PC display:

3 EXTREMELY BETTER, 2 QUITE BETTER or 1 SLIGHTLY BETTER

0 SAME

-1 SLIGHTLY WORSE, -2 QUITE WORSE or -3 EXTREMELY WORSE

1 How better or worse is the visual experience vs benchmark?

Visual Experience							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
SIM2							
HTC VIVE							
OCULUS GO							

2 How would you rate the image detail vs benchmark?

Image Detail							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
OCULUS GO							
SIM2							
HTC VIVE							

3 How much better or worse would you say the advantage of working with each is vs benchmark?

Advantage Over Benchmark							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
HTC VIVE							
OCULUS GO							
SIM2							

4 In terms of usability, how would you rate each one of them vs Benchmark?

Usability							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
SIM2							
OCULUS GO							
HTC VIVE							

5 How much better or worse is the display performance (E.g. brightness, contrast, colour, sharpness)

 vs benchmark?

Visual Performance							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
OCULUS GO							
HTC VIVE							
SIM2							

6 How useful/valuable is the immersive proposition of each display vs benchmark?

Immersive Value							
	Extremely Less Useful	Less Useful	Slightly Less Useful	Same	Slightly More Useful	More Useful	Extremely More Useful
	-3	-2	-1	0	1	2	3
HTC VIVE							
SIM2							
OCULUS GO							

7 How would you rate the 360 experience on each display vs benchmark?

User Experience							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
OCULUS GO							
HTC VIVE							
SIM2							

8 How useful do you find 360 visualisations on each display for design review?

Value For Design Review							
	Extremely Less Useful	Less Useful	Slightly Less Useful	Same	Slightly More Useful	More Useful	Extremely More Useful
	-3	-2	-1	0	1	2	3
HTC VIVE							
SIM2							
OCULUS GO							

9 How appealing/emotional is each output compared with the benchmark?

Appeal / Emotion							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
SIM2							
HTC VIVE							
OCULUS GO							

10 How beneficial would this technology be for visual aids in an engineering/design environment?

Tech Benefit On Workflow							
	Extremely Benefitial	Benefitial	Slightly Benefitial	Same	Slightly Benefitial	Benefitial	Extremely Benefitial
	-3	-2	-1	0	1	2	3
HTC VIVE							
SIM2							
OCULUS GO							

11 How engaged/involved did you feel with each output compared with the benchmark?

Engagement Level vs Benchmark							
	Extremely Less Engaged	Less Engaged	Slightly Less Engaged	Same	Slightly More Engaged	More Engaged	Extremely More Engaged
	-3	-2	-1	0	1	2	3
HTC VIVE							
OCULUS GO							
SIM2							

12 How would you rate the functional value (for design review) of each display vs benchmark?

Functional (design review) Value							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
HTC VIVE							
OCULUS GO							
SIM2							

13 How would you rate each technology for aesthetic communication vs benchmark?

Aesthetic Value For Communication							
	Extremely Worse	Worse	Slightly Worse	Same	Slightly Better	Better	Extremely Better
	-3	-2	-1	0	1	2	3
HTC VIVE							
OCULUS GO							
SIM2							

Part 2

14 If you were/are the decision maker, how likely would you adopt this technology?

Tech Adoption Likelihood							
	Extremely Unlikely	Unlikely	Slightly Unlikely	Same	Slightly Likely	Likely	Extremely Likely
	-3	-2	-1	0	1	2	3
SIM2							
HTC VIVE							
OCULUS GO							

15 What is the level of exposure you have had to each technology in the past?

Exposure To Tech							
	Extremely Less	Less	Slightly Less	Same	Slightly More	More	Extremely More
	-3	-2	-1	0	1	2	3
SIM2							
OCULUS GO							
HTC VIVE							
Full Virtual Reality							

16 Rank each visual output according to each product development phase, 4 being the best option

and 1 as the worst of them.

NPD Process					
	Concept creation	Design development	Design Testing/Review	Design approval	Design / eng. Communication
HTC VIVE					
OCULUS GO					
SIM2					
Full Virtual Reality					

17 Do you think the immersive tools would offer more value than the current ones?

Yes_____   No_____

18 If yes, in which way would they provide this value or benefit?

_____

___

19 How would you like to see these tools deployed and integrated into JLR's engineering process?

_____

20 If you don't think they would be useful, do you think future, enhanced versions would offer this

value / benefit? Why?

_____

21 Do yo know other people within JLR who could benefit from these technologies?

Yes_____   No_____

22 Would you recommend the use of HMDs to colleagues?

Yes_____ No_____

23 Would you be confident using VR hardware in an office environment? (e.g. wearing an HMD next

to your colleagues)

Yes_____ No_____

24 Would you be confident to use VR equipment and run your own tests in this environment?

Yes_____ No_____

25 Comments or observations concerning the use of each output for the Technology Value

Proposition in the new product development process.

Open Comment Tech Value	
HTC VIVE	
OCULUS GO	
SIM2	
Full Virtual Reality	

If you want more information on JLR's current engineering visualisation

capabilities please contact ███████████████████████

Appendix G. Trial subjects

Subject	Age	Role	Engineering purpose for visualisation technology	Purpose
1		Vehicle Packaging		Vision comparisons
2		Interior Vehicle packaging	Package investigation/ HF, ext vision, etc.	Geometry visualisation, vision studies, etc.
3		Human factors PAT Leader	Speos	Vision, pano roof
4		Vehicle Packaging Zone Leader	Package + Ergo	Vision, ergo reviews
5		Packaging	Interior roominess	Interior roominess evaluation
6				
7		Human Factors Specialist	Requirement validation and product development	Vision
8		UP Package Engineering	Geometry review / Customer use cases / Ext. loading / Trunk	Exterior vision / Geometry review
9		Human Factors Engineering	Assessment & Verification	Vision assessments / Packaging
10		Optical CAE Specialist	Optical review	Manufacturing and packaging
11		Vehicle Packaging	Benchmarking / Understanding of designs	Design reviews / Benchmarking user experience
12				
13		Human Factors	Feature demos	Intro session to department
14		Virtual Reality Engineer (CAVE)	Engineering support	I run it !
15		Subject Matter Expert (for vision)	Assess exterior vision	Exterior vision
16		Human Factors SME	Commodity development and evaluation	Reviews / Evaluation / HMI prototyping
17		Human Factors Practicality SME	Console layout / Visibility / Practicality assessments	Practicality assessments
18		OCAE Engineer		
19		OCAE Analyst	Optical quality check	To compare SPEOS result with visualisation
20		Optical CAE Lead	Optical failure identification	
21		Optical CAE		
22		Human factors PAT	Surface assessments, vision, glare, DLU	Vision and practicality reviews
23		Human Factors Physical Usability SME		Assess rim block
24		Package Engineer	Overall vision	Vision
25		Lighting PRE P.S. Int/Ext	Assessing interior illumination and visual night drives	Working on a project with the V.I.D. team
26		Package Team Leader	Vision / Ergo	Vision
27		Virtual Visualisation Engineer	Central team for visualisation capability	Immersive CAD visualisation
28		Technologist		Testing / review
29		Human Factors Lead	Reflection assessment / veiling glare	Surface reviews / All around vision
30		Human Factors SME	Roominess SME	Vision / roominess assessment
31		Human Factors Specialist	Vision reviews, ergonomic comparisons	Vision reviews

Appendix H. Ricoh Theta V Specification Sheet

THETA V

Release date	9/2017
External dimensions	45.2×130.6×22.9(mm)
Weight	Approx. 121 g
Still image performance	5376×2688 pixels
Video performance	4K 3840×1920 pixels/29.97fps/56Mbps 2K 1920×960 pixels/29.97fps/16Mbps Maximum continuous recording time: 25 minutes
Live streaming performance	4K H264: 3840×1920 pixels/29.97fps 2K H264: 1920×960 pixels/29.97fps
Microphone	4ch
Display panel	-
Internal memory	Approx. 19GB Still image: (JPEG) Approx. 4800 photos Video: Approx. 40 minutes
Compatible accessories	Tripod/stand (includes tripod mount hole) Waterproof case (TW-1) 3D microphone (TA-1)
Bundled items	Soft case and USB cable

-Built-in function-

High speed power on / RAW (DNG) recording / Aperture priority shooting / Self-timer shooting / Remote shooting / Preset / Noise reduction shooting / DR compensation shooting / HDR rendering shooting / Interval shooting / Interval composite shots / Multi bracket shooting / Zenith correction / Position information memory / Image stabilization / 360 spatial audio / Wireless LAN high speed transfer / Wireless LAN connection (direct mode) / Wireless LAN connection (client mode) / Equipped with Bluetooth / Plug-in support

Specifications

Image sensor:

    1/2.3 CMOS (Effective pixels: Approx. 12.0 megapixels) × 2

File size (still images):

    5376 × 2688

File size and frame rate (videos):

    3840 × 1920, 29.97 fps

    1920 × 960, 29.97 fps

File size and frame rate (live streaming):

    3840 × 1920, 29.97 fps

    1920 × 960, 29.97 fps

Lens:

    Aperture: F2.0

    Lens construction: 7 elements in 6 groups × 2

Capture mode:

    Still image: Auto, Shutter priority, ISO priority, Manual (*1)

    Video: Auto

    Live streaming: Auto

Shooting distance:

    Approx. 10 cm to ∞ (from front of lens)

Exposure control mode:

    Program AE, Shutter speed priority AE, ISO sensitivity priority AE, Manual exposure (*1)

Exposure compensation:

    Manual compensation (-2.0 to +2.0 EV, 1/3 EV steps) (*1)

ISO sensitivity (standard output sensitivity):

    Still image: ISO 64 to 1600 (Auto), ISO 64 to 3200 (ISO priority, Manual) (*1)

    Video: ISO 64 to 6400

    Live streaming: ISO 64 to 6400

White balance mode:

    Still image: Auto, Outdoor, Shade, Cloudy, Incandescent light 1, Incandescent light 2, Daylight color fluorescent

    light, Natural white fluorescent light, White fluorescent light, Light bulb color fluorescent light, Color temperature

    settings (2500 to 10000 K) (*1)

Video: Auto

Live streaming: Auto

Shutter speed:

Still image: 1/25000 to 1/8 seconds (Auto), 1/25000 to 15 seconds (Shutter priority), 1/25000 to 60 seconds

(Manual) (*1)

Video: 1/25000 to 1/30 seconds

Live streaming: 1/25000 to 1/30 seconds

Recording medium:

Internal memory: Approx. 19 GB

Number of images that can be recorded and recording time (*2):

Still image: Approx. 4800 images

Video (time per recording): Max. 5 or 25 minutes (*1) (*3)

Video (total recording time): Approx. 40 minutes (4K, H.264), approx. 130 minutes (2K, H.264)

Power source:

Lithium ion battery (built-in battery) (*4)

Battery life:

Still image: Approx. 300 images (*5)

Video: Approx. 80 minutes (*5)

Image file format:

Still image: JPEG (Exif Ver. 2.3)

Video: MP4 (Video: MPEG-4 AVC/H.264, Audio: AAC-LC (mono) + Linear PCM (4ch spatial audio))

Live streaming: (Video: H.264, Audio: AAC-LC (mono))

Other:

Self-timer shooting, Interval shooting, Multi bracket shooting

External interface:

Micro-USB terminal: USB 2.0

Microphone terminal (*6)

Bluetooth® accessory:

Compatible with Bluetooth® HID devices

Remote release:

CA-3 (optional)

Dimensions:

45.2 mm (W) × 130.6 mm (H) × 22.9 mm (17.9 mm (*7)) (D)

Weight:

Approx. 121 g

Operating temperature range:

0 to 40°C (0 to 104°F)

Operating humidity range:

90% or less

Storage temperature range:

-20 to 60°C (-4 to 140°F)

(*1)
A smartphone is required to change modes or configure manual settings.

(*2)
The number of images and time are guides only. The actual number differs according to the shooting conditions.

(*3)
Recording stops automatically if the internal temperature increases.

(*4)
Charge the battery by connecting it to a computer using the provided USB cable.

(*5)
The number of images that can be taken is a guide based on RICOH's measurement method. The actual number differs according to the usage conditions.

(*6)
Do not connect any device other than the 3D microphone TA-1 to the microphone terminal.

(*7)
Excluding lens section.