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Digitalisation Expert Group White Paper

Immersive simulation and XR in the automotive industry:
state of the art and challenges



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Executive summary

Immersive simulation in the automotive industry is reshaping approaches to vehicle design and engineering. Extended Reality (XR) and visual simulation, particularly human-in-the-loop, multi-sensory experiences that combine high-fidelity rendering, accurate material and lighting models, and interactive workflows are changing design, validation, manufacturing, and customer evaluation.

This white paper defines key concepts, surveys the state of the art in XR devices, graphics, data, and standards, and illustrates value through representative automotive use cases. The paper aims to align stakeholders on terminology, capabilities, and challenges, outlining a pragmatic outlook for XR adoption through 2035.

Immersive simulation is a strategic evolution of numerical simulation, shifting from physics-only CAE toward holistic, customer-centric experiences that place humans directly inside virtual or hybrid environments. Immersive simulation puts humans in the simulation loop, representing their use of the future vehicle during the various phases of design, development, production, or even marketing and after-sales. This human-in-the-loop approach enables intuitive evaluation, cross-disciplinary communication, and early-phase decision-making at vehicle level.

With clarity in the definitions across VR, AR, MR, spatial computing, and the Metaverse, it becomes easier to see how XR enables credible perception through real-time responsiveness, multisensory feedback, and natural interaction. But the technological landscape is still shifting: XR devices, haptics, computer graphics pipelines, light-matter physics, global illumination, 3D data standards (including OpenUSD), and the growing role of AI in generating virtual environments are all changing the role and importance of technology.

A series of automotive use cases demonstrates XR's tangible value, from lighting simulation and perceived-quality reviews to manufacturing ergonomics, CMF visualisation, aerodynamics development, and powertrain CAE immersion. These examples show how XR reduces lead time, enhances collaboration, lowers design costs, and improves customer-experience evaluation.

Looking forward, XR's trajectory will continue to evolve; the importance of open standards, ecosystem collaboration, and AI-accelerated workflows will grow. Immersive simulation is positioned not as an optional tool, but as a critical capability for future automotive development.

Chapter 1: Introduction

The automotive industry is rapidly evolving with the integration of electrification, connectivity, and advanced driver assistance systems (ADAS). These innovations are transforming vehicles into complex, intelligent systems that interact dynamically with their environment. The automotive industry is facing major challenges bringing products to market quickly, and with greatly reduced design and validation costs.

As a result, manufacturers must explore the use of new digital tools, such as simulation and artificial intelligence, while capitalising on the user experience by leveraging vehicle data. The trend is toward customer centricity: the customer is at the heart of the design process, and the validation tools being used must meet this expectation.

Immersive simulation is part of the wider "numerical simulation" family. Historically, numerical simulation (Computer Aided Engineering, or CAE) has been addressing the capability to model and simulate some of the physics of the vehicle, e.g. vehicle dynamics, aerodynamics, acoustics, mechanical structure, but also passive safety, materials, and more.

The immersive simulation being discussed in this paper is another approach, one that puts humans in the simulation loop, representing their use of the future vehicle during the various phases of design, development, production, or even marketing and after-sales. This is an area of simulation that can be described as "end-to-end." It also includes optical simulations that predict appearance based on the interaction of light with materials.

So, what makes immersive simulation unique from other simulations?

Firstly, as briefly introduced, a simulation is said to be immersive if it puts the human in the loop. The human may be the driver in action, or the customer using the product. Therefore, consider technologies that allow humans to be immersed in the environment, but also allow interaction with the product. Thus, we can refer to either immersive simulation or interactive simulation. Including humans in the loop offers a significant advantage: it allows anyone, even non-specialists or those with diverse skills and expertise to engage directly with the product and obtain understandable results. Immersive simulation serves as an excellent tool for communication and alignment.

Then, an immersive simulation will consider the product in its entirety, sometimes referred to "at the vehicle level" (in the automotive field), as opposed to simulating systems or components. This is where the value of putting humans in the loop comes in – designing the simulation experience around the customer and their interaction with the vehicle.

Immersive simulation is sometimes referred to as synthesis simulation because, by putting humans in the loop, it can demonstrate performance or characteristics that provide a synthesised view of several domains or criteria. In a traditional V-cycle development approach, it is positioned at the top of the cycle, in the requirements definition and scoping phases, and in the product validation and even certification phases.

Another way to characterise immersive simulation is to note that it aims to mimic physical and visual presence to provide credible experiences. To achieve this result, it uses a multi-sensory approach. While immersive

simulation has historically relied mainly on the sense of sight, it is also capable of incorporating physical elements that allow the human being to be positioned correctly in the vehicle and interact with the product or its environment: examples include instrumented seating bucks and the use of steering wheels or pedals, which are the points of interaction between the driver and the vehicle. Some systems can produce haptic feedback, whether vibratory or tactile, or even the sensation of touch or effort. Another widely used sense is sound, which can be spatialised to reproduce all the acoustic cues inside the vehicle, for example when driving. More rarely, there are prototype systems that provide olfactory feedback, but these are still quite specialised.

What is sought is embodiment and a sense of presence. Ultimately, immersive simulation can be seen as providing a holistic experience of the vehicle's systems and functionalities.

Immersive simulation encompasses a broad range of technologies designed to create realistic and interactive virtual environments:

- **Extended Reality (XR)** forms the foundation, combining Virtual Reality, Augmented Reality, and Mixed Reality to deliver engaging experiences for training, design, and collaboration. Within this domain, users can interact with digital twins and complex systems in a fully immersive context.
- **Driving Simulation** focuses on replicating real-world vehicle dynamics, traffic scenarios, and environmental conditions to support driver training, safety validation, and autonomous system development. It enables precise modelling of human behaviour and advanced control systems under varied conditions.
- **Visual Simulation** underpins these experiences by providing high-fidelity rendering and optimised algorithms for large-scale simulations. This domain ensures photorealistic environments, accurate lighting, and accurate material representation.

In this initial version of the document, we will focus on Extended Reality (XR) technologies and introduce the field of Visual Simulation. Future iterations may expand the scope to encompass Driving Simulation.

This white paper provides a comprehensive overview of immersive simulation technologies applied to the automotive industry. It begins by defining key concepts and presenting the current state of the art, highlighting how these technologies are evolving and the major challenges that remain. Beyond the theoretical framework, the document explores typical applications of immersive simulation through real-world use cases and technical insights, illustrating its tangible impact on the design, validation, and development of current and next-generation vehicles. Finally, the paper offers a forward-looking perspective on market trends and potential breakthroughs, projecting the role of immersive simulation in the automotive sector by 2035.

> *Immersive simulation puts humans in the loop, enabling anyone to engage directly with the product, experience future vehicles before they exist, and validate design decisions through realistic, interactive environments that bring engineering, technology and customer experience together.*

Chapter 2: Definitions

2.1 Common vocabulary

As XR technologies mature and diversify, the terminology surrounding them has become increasingly fragmented, with overlapping definitions and inconsistent usage across research, engineering, and commercial domains. Clear, shared definitions are therefore essential: they enable alignment between OEMs, suppliers, and technology partners, and ensure that immersive simulation workflows are built on a common understanding of how real and virtual environments interact.

This chapter clarifies the perimeter of Extended Reality (XR) by examining its constituent technologies – virtual reality, augmented reality, mixed reality – and the broader concepts that shape modern immersive systems, including spatial computing and the Metaverse. It also introduces the notion of human-in-the-loop simulation, a defining characteristic of immersive approaches in automotive development.

By establishing precise definitions and highlighting areas where the literature diverges, this chapter provides a structured framework for interpreting the technologies, capabilities, and use cases explored later.

2.2 Overview

Immersive simulation encompasses several advanced technologies aimed at creating interactive, immersive environments for users. These technologies include virtual reality (VR), augmented reality (AR), and mixed reality (MR), as well as other forms of simulation in which the human being plays a central role, such as driving simulation. Sometimes the term interactive simulation is also used.

Virtual reality (VR) enables users to immerse themselves in fully digital worlds using virtual reality headsets. These environments can be replicas of real places or imaginary environments, offering a complete sensory experience including sight, but also sound, and sometimes even touch.

Augmented reality (AR) superimposes digital elements on the real world. Used via smartphones, tablets, or augmented reality glasses, this technology enriches our perception by adding information or virtual objects to our immediate environment.

Mixed reality (MR) combines aspects of VR and AR to create environments where virtual and real objects can interact dynamically. This technology enables advanced applications such as overlaying an interactive virtual instrument panel or UI screen on a static physical seating buck.

Driving simulation (Driver-in-the-Loop, or DIL) is a valuable tool for automakers, who use it to test new driver assistance systems (ADAS), human-machine interfaces and various customer services. These simulators reproduce vehicle driving conditions with a high degree of realism. Thanks to dynamic virtual environments, haptic interfaces, force feedback systems, and interactive scenarios, users can experience various situations without the risks associated with real-life driving.

Driving simulation is a perfect illustration of the "human-in-the-loop" concept, where interaction between the user and the system is at the heart of the experience. It combines technical aspects (physical modelling, graphic rendering, sensors) and human aspects (perception, decision-making, learning), making this field a pillar of modern immersive simulation.

The scope of immersive simulation is vast and constantly evolving. Technological advances continue to push back the boundaries of what is possible, making immersive experiences increasingly realistic and interactive.

2.3 Defining Extended Reality

Immersive technologies are transforming the way we interact with digital environments. Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), each offer distinct approaches to blending physical and virtual worlds. Alongside these, emerging concepts such as spatial computing and the Metaverse push the boundaries even further, enabling intelligent environments and shared virtual spaces. This chapter explores these technologies in detail, clarifying their definitions, differences, and the opportunities they create for realistic and interactive experiences.

2.3.1 Milgram's continuum

The continuum of Milgram and Kishino remains a reference today for defining the concepts of MR, VR, and AR. As shown in Fig. 1, Milgram's real-virtual continuum is a structure that describes a spectrum of environments ranging from a full physical and real environment to a completely virtual environment. This continuum allows for categorising the different forms of interactions between the real and the virtual based on their composition.

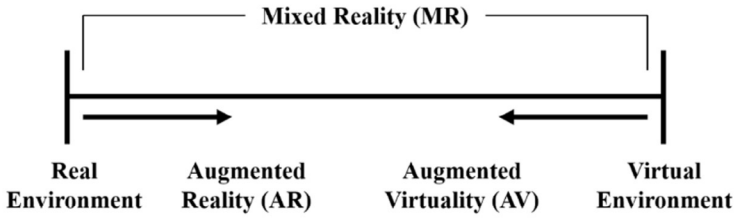


Fig. 1 Adapted from Milgram and Kishino's Reality–Virtuality Continuum (1994).

The main notions are based on the following:

- **Real Environment:** A real environment consists of physical objects only, without any intervention or overlay of digital elements. In this context, the user interacts exclusively with the tangible world, without any additional virtual content.
- **AR:** Augmented reality is a subcategory of mixed reality, where a real environment is enriched by virtual content. These digital elements are overlaid on the physical world, thus augmenting the user's perception of reality without obscuring the real environment.
- **AV:** Like augmented reality, augmented virtuality refers to primarily virtual environments in which some real objects are integrated. Here, the virtual world predominates, but it is punctuated by the presence of physical elements, allowing partial interaction with the real world.
- **Virtual Environment:** A virtual environment consists exclusively of digital objects, without any physical component. In this setting, the user is completely immersed in a virtual world, disconnected from physical reality, with interaction only with computer-generated elements.

- **MR:** Mixed reality encompasses all environments that combine real and virtual elements, displayed simultaneously on the same device. In such an environment, physical and digital objects coexist and interact in real time.

The linear framework of Milgram's real-virtual continuum helps to understand and to categorise the various forms of mixed reality, depending on the degree of mixing between the real and the virtual.

2.3.2 Augmented Reality

In the literature, AR is defined in various ways, although a core for all these definitions seems to be a combination of virtual objects into real environments. AR is often described as an overlay of digital elements onto the real world, thereby enriching the user's experience. This broad definition encompasses all forms of digital augmentation that modify or enhance the perception of the real world, without necessarily specifying the nature of this overlay.

Another definition of AR involves the integration of 3D graphical visuals into the real world, while considering the user's physical environment. This approach requires precise spatial understanding, where digital elements are aligned and interact coherently with the physical setting. This definition of AR, which includes projection mapping, has been largely democratised by AR smartphone applications.

Finally, a third, broader possible definition of AR is a blend of human, digital, and physical worlds. Here, active user interaction with the simulation is essential, as well as control over the augmented elements while still considering the user's physical environment.

From these three main definitions, two contradictory statements emerge. The first is that simple contextual overlays are sufficient for AR, if they are relevant and contextual to the user's environment. The second statement is that AR requires spatial knowledge of the user's physical environment as well as interactions between this environment and the virtual content. These differences show that, although the concept of augmented reality is widely recognised, there are still debates regarding the specific criteria that define it.

2.3.3 Virtual Reality

VR is mainly described as an experience in which the user is immersed in a computer-generated virtual environment with tracked vision to match head movements and vision is entirely virtual. Another commonly shared characteristic of VR highlights user isolation: the user is isolated from the physical world, which may enhance immersion but limits the possibilities for social interactions with other users, unless the other users are incorporated as virtual avatars.

Finally, a third specificity highlights the visual aspect of VR, defining it as a fully virtual immersive experience, realised through head-mounted technologies such as virtual reality headsets. This definition focuses solely on that specific type of hardware, particularly on the device's ability to offer an immersive and interactive view with three to six degrees of freedom of movement.

These different definitions illustrate a certain concordance of approaches to understand virtual reality: a 100% virtual, visual, immersive view with head-mounted technologies. However, this vision is strongly based on the hardware and the visual aspect of the user experience. It fails to capture the broader and evolving concepts of VR, such as multisensory, collaborative, and social interactions.

2.3.4 Mixed Reality

The state of the art reveals a diversity of characteristics of MR, reflecting varied and often contradictory perspectives on this concept. A widely recognised definition of MR is based on the real-virtual continuum of Milgram and Kishino, a diagram defining visual composition of MR environment simulations.

According to this approach, MR is a blend of physical and virtual environments on a single display, covering a spectrum that ranges from completely real to completely virtual. This mix encompasses augmented reality and augmented virtuality (AV). VR is not part of the original continuum, although it is considered by some to be encompassed within MR definition.

Another controversial definition considers AR and MR as identical and interchangeable terms, with MR being seen as just a buzzword used for marketing purposes. According to this perspective, MR does not represent a distinct concept but rather a reinvention of AR under another name.

MR is also described as a form of collaboration, where it constitutes the space or dimension of interaction between users in AR and/or VR, but physically separated.

This definition highlights MR ability to enable interactions between real and virtual environments remotely. It includes MR capacity to map spaces and users, and to reconstruct it virtually from another place. Another perspective sees MR as a combination of AR and VR technologies. It refers to a system that uses elements of AR and VR simultaneously or can switch between these two modes. This definition is more technology centred as it is often used to describe an app or a device, for example a 360° photo application that uses marker-based AR to add real objects inside a VR Store.

Some authors define MR as the precise collocation of a virtual environment with a physical environment, allowing for coherent interactions between the two. This includes the use of tracking systems to collocate virtual objects to their physical counterpart, as well as 3D sensors that allow spatial-mapping and virtual real-time re-projection of real environments.

Finally, another approach describes MR as an advanced version of augmented reality. It is characterised by a better awareness of the physical environment and more sophisticated interactions with it.

The state-of-the-art shows that it is particularly difficult to define what constitutes MR, due to many contradictions among the different definitions. This diversity of definitions highlights the need for ongoing conceptual clarification in this field, as the technologies and applications of MR continue to evolve. However, the most accepted notion remains in the real-virtual continuum, which is considered the most used and quoted definition in literature.

2.3.5 Extended Reality

The literature shows that XR is primarily defined as a generic term that encompasses several immersive technologies, including AR, VR as well as 360° videos, and MR.

XR has the capacity to group various technologies that allow for combining real and virtual content. One of the major objectives of XR, as defined in the literature, is to create a "digital twin" of the physical world. Extended reality is designed to faithfully reflect the real world and enable dynamic interaction between the two. However, this definition has no universal support. Showing that XR is a broad and flexible concept, encompassing all immersive technologies that combine reality and virtual experiences.

2.3.6 Spatial Computing

The concept of spatial computing has evolved to become a key term describing a range of emerging technologies. Greenwold initially defined spatial computing as "human interaction with a machine in which the machine retains and manipulates references to real objects and spaces." This definition emphasises the machine's ability to understand and interact with the physical world in a way that integrates real objects and spaces into computing processes. Modern definitions describe spatial computing as a set of technologies that "digitise the activities of machines, people, and objects as well as the environments in which they occur."

This approach shows the capacity of these technologies not just to understand but to capture, model, and interact with elements of the physical world in a digital environment. Microsoft describes spatial computing as "the device's ability to be aware of their environment and to digitally represent it", while Apple states that spatial computing "seamlessly blends digital content with the physical world."

Spatial computing is also defined as encompassing any techniques, primarily associated with AR, VR, artificial intelligence (AI), and the Internet of Things (IoT), allowing for human-computer interaction perceived by the user as occurring in the real world, not in a strictly digital world. This suggests that these interactions are designed to appear natural and integrated into the physical environment.

Finally, spatial computing is sometimes described as a convergence of AI and the Metaverse, combining advanced data processing capabilities and immersive virtual environments to create sophisticated interactive experiences. While being introduced around 1985 to describe computation on large scale geospatial data, spatial computing is a modern concept that encompasses a wide range of new technologies and technics aimed at integrating physical and digital environments and improving the way machines perceive and interact with the real world.

2.3.7 Meta Reality or Metaverse

The concept of Meta Reality, or Metaverse, has become central in discussions about the evolution of the Internet and digital environments. The Metaverse was first characterised as three-dimensional persistent virtual worlds where users can interact in real time, meet, and collaborate.

Since the early 2020s, the term Metaverse has often been linked to immersive digital experiences. Another definition emphasises the merger between the physical and digital worlds within the Metaverse. This merger aims to create interactive experiences where the boundaries between virtual and real environments become blurred, where physical and digital realities coexist and interact fluidly.

Finally, the social aspect of Metaverse is also an important component, with user interactions, most often through avatars, making the Metaverse a deep social and community space.

Metaverse is envisioned as a major evolution of the internet, including new types of commerce, non-fungible tokens, blockchain, and more. However, its main attributed characteristic is being a persistent and collaborative 3D virtual environment. However, it is loosely defined, and variants have appeared, making the Metaverse definition increasingly heterogeneous.

2.4 Human-in-the-loop / interactive simulation

For automotive industry use cases, the major need is to immerse the user in a virtual or hybrid world, enabling perception and actions found in the real world. XR technology is the closest capability the industry has today to accurately simulate human perception and behaviour. Furthermore, XR allows technicians to simulate real-life situations that would be too difficult, risky, or expensive to reproduce in the real world.

Lastly, the user can immediately perceive the experience a customer or operator will have in the future with the product. Unlike typical CAE simulations that only offer a third-person perspective, XR enables a user centric first-person experience.




***Fig. 2** Immersion in a virtual world and interaction with the car, courtesy of Stellantis.*

Delivering a truly effective first-person simulation requires the seamless integration of three essential components:

- **Immersive sensory experience** in a virtual environment (see Fig. 2): vision is the most critical sense, complemented by hearing and haptic feedback. Smell and taste are outside the scope of our use cases.
- **Natural interaction** within the virtual world: this includes both human movements and the dynamic behaviour of virtual objects, whether triggered by the user or by other factors.
- **Real-time responsiveness:** for immersion and interaction to feel authentic, the system must operate in real time, or at least at a speed perceived as real by the user. Otherwise, the sense of presence will degrade. For example, visual rendering should reach around 60 Hz, while haptic feedback requires approximately 1 kHz.

When these three components are delivered simultaneously at the right quality level, the virtual environment can closely approximate reality, resulting in user behaviour that mirrors real-world conditions (Fig. 3).




***Fig. 3** Cockpit architecture simulation, courtesy of Stellantis.*

2.5 Computer Graphics

2.5.1 Computer Graphics - definition

Computer Graphics (see Fig. 4) refers to the use of computational resources and algorithms to generate, manipulate, and render visual content, typically in the form of 2D or 3D images, animations, and simulations. It encompasses:



***Fig. 4** Computer graphics, courtesy of Renault.*

Graphics Pipeline Operations

The graphics pipeline is a sequence of stages that converts abstract data into a final image. It begins with modelling, where 3D objects are defined using geometric primitives. Next comes shading, which applies material properties and lighting calculations to give surfaces a realistic appearance. From the point of view of the graphic calculation algorithm, virtual reality is most often based on OpenGL type technologies, qualified as realistic real-time rendering, which produces the image according to a process called rasterization. This process transforms these 3D representations into 2D fragments suitable for display. Finally, the rendering process assembles all elements – geometry, textures, and lighting – into a coherent visual output.

Hardware Acceleration

Modern rendering relies heavily on GPUs (Graphics Processing Units), which are optimised for parallel computation. This architecture enables simultaneous processing of thousands of operations, making real-time rendering and advanced effects like reflections and shadows feasible. Hardware acceleration is essential for interactive applications such as virtual reality and immersive simulations.

Mathematical Foundations

Underlying these processes are robust mathematical techniques. Vector and raster graphics define shapes and pixel grids, while ray tracing simulates light paths for photorealism. Advanced methods like photon mapping and global illumination model complex light interactions. These rely on principles from linear algebra, geometry, and optics, forming the backbone of computer graphics.

Performance Constraints

Achieving smooth performances such as 60 frames per second (FPS) –requires balancing speed with visual fidelity. Physically accurate light transport models are computationally expensive, so developers often make trade-offs. Techniques like level-of-detail rendering, approximation algorithms, and adaptive sampling help maintain real-time responsiveness without sacrificing too much realism.

2.5.2 Light–matter interactions

Light–matter interactions encompass the range of physical phenomena that occur when electromagnetic radiation interacts with matter. These processes include absorption, emission, scattering, reflection, refraction, and nonlinear effects. They govern the transfer of energy between photons and material systems, influencing electronic, vibrational, and structural properties.

These interactions form the physical foundation for graphics computation, where simulated physics is essentially the behaviour of light. In computer graphics applications, light simulation is always involved – though at varying levels of complexity and computational precision.

White light and its composition

White light is not a single colour, but a combination of all wavelengths within the visible spectrum (see Fig. 5), ranging approximately from 380 nm (violet) to 780 nm (red). Each wavelength corresponds to a different perceived colour, and together they create what we call "white" light.

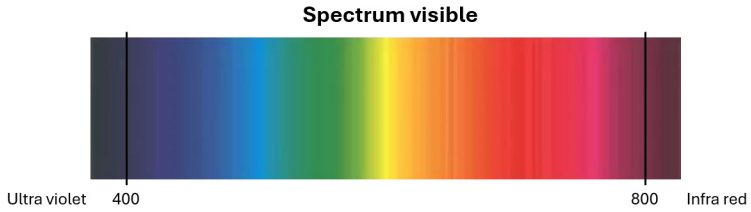


***Fig. 5** Visible light spectrum (380–780 nm), educational diagram.*

Light-matter interaction

When light encounters a material (see Fig. 6), several interactions can occur: reflection, absorption, transmission, or scattering. Which interaction dominates depends on two main factors: the wavelength of the incident light and the angle at which it strikes the surface. For example, shorter wavelengths may scatter more strongly, while longer wavelengths might penetrate deeper.

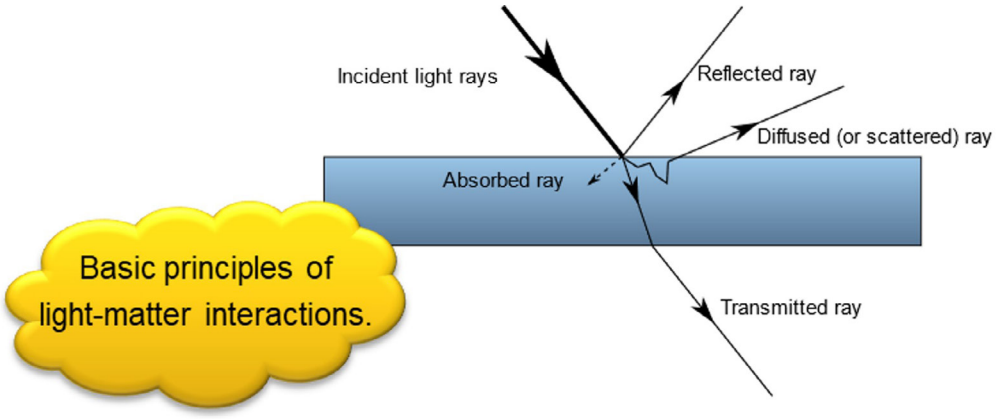


***Fig. 6** Light matter interactions simplified model, educational diagram.*

Secondary rays and perception

After the initial interaction, the material emits or reflects secondary rays toward the observer. These rays carry only certain wavelengths, depending on the material's properties. If most blue wavelengths are reflected and others absorbed, the object appears blue to us. Conversely, if all wavelengths are reflected equally, the material looks white.

Appearance to the human eye

Our perception is determined by which of these secondary rays reach our eyes and stimulate the three types of cone cells sensitive to red, green, and blue. The brain combines these signals to reconstruct the colour impression. Thus, the apparent colour of an object is not an intrinsic property, but the result of complex light-matter interactions and human visual processing.

Light modelling

The General Reflectance Function (GRF) (see Fig. 7) is a theoretical model designed to describe how light interacts with a surface under all possible conditions. It is a 16-dimensional function, meaning it accounts for numerous variables such as the direction and wavelength of incoming light, the viewing direction, polarisation states, and even time-dependent factors. This complexity allows the GRF to represent the most complete description of a material's optical behaviour.

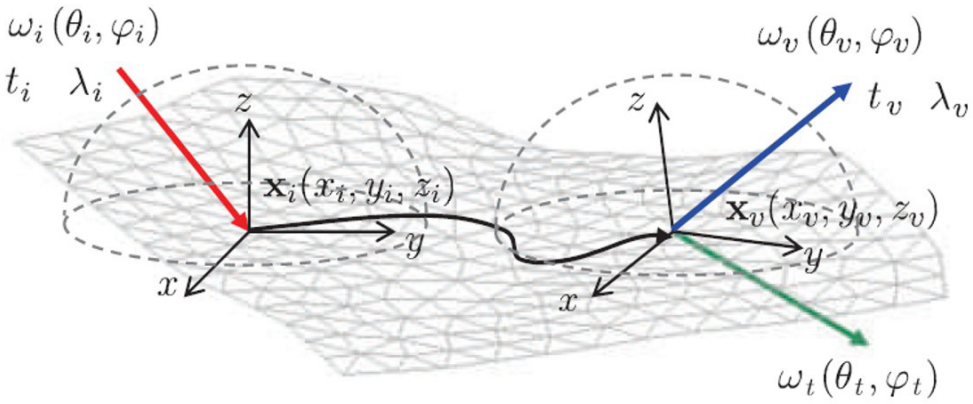


***Fig. 7** General reflectance function illustrating spatial, angular, spectral and temporal dependencies (after Haindl & Filip, 2013).*

However, such a model is extremely impractical in real-world applications. Capturing data for all these dimensions is beyond the capability of any existing measurement system, as it would require an astronomical number of samples. Even if such data were available, it would be useless for current rendering engines, which cannot process or exploit such high-dimensional datasets efficiently. Moreover, for most materials, this level of detail is irrelevant, since their appearance can be approximated accurately using simpler models like BRDF or BSDF.

In practice, computer graphics rely on these simplified models to balance realism with computational feasibility.

Example (see Fig. 8):

- **VR** relies on a simplified light model, enabling real-time calculations for immersive experiences at a natural scale.
- **Visual Simulation** employs a more sophisticated light model, ensuring that the simulation closely predicts how the physical product will appear to the customer.

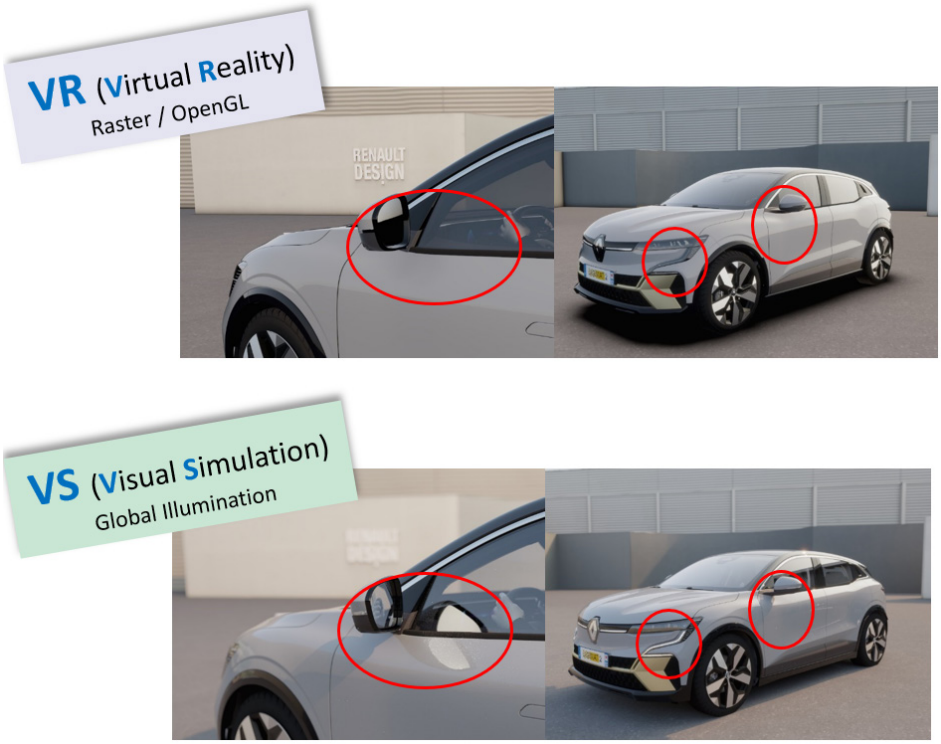


***Fig. 8** Virtual Reality versus Visual Simulation, courtesy of Renault Group.*

2.5.3 Rendering versus perception

A digital screen, regardless of its quality, imposes inherent limitations when displaying simulated phenomena. It acts as a kind of low-pass filter between the simulation and human perception, meaning that fine details, extreme contrasts, and subtle variations in light and colour are often lost or smoothed out (see Fig. 9). This filtering effect occurs because screens have finite resolution, restricted colour reproduction, and limited brightness range compared to the complexity of real-world lighting.

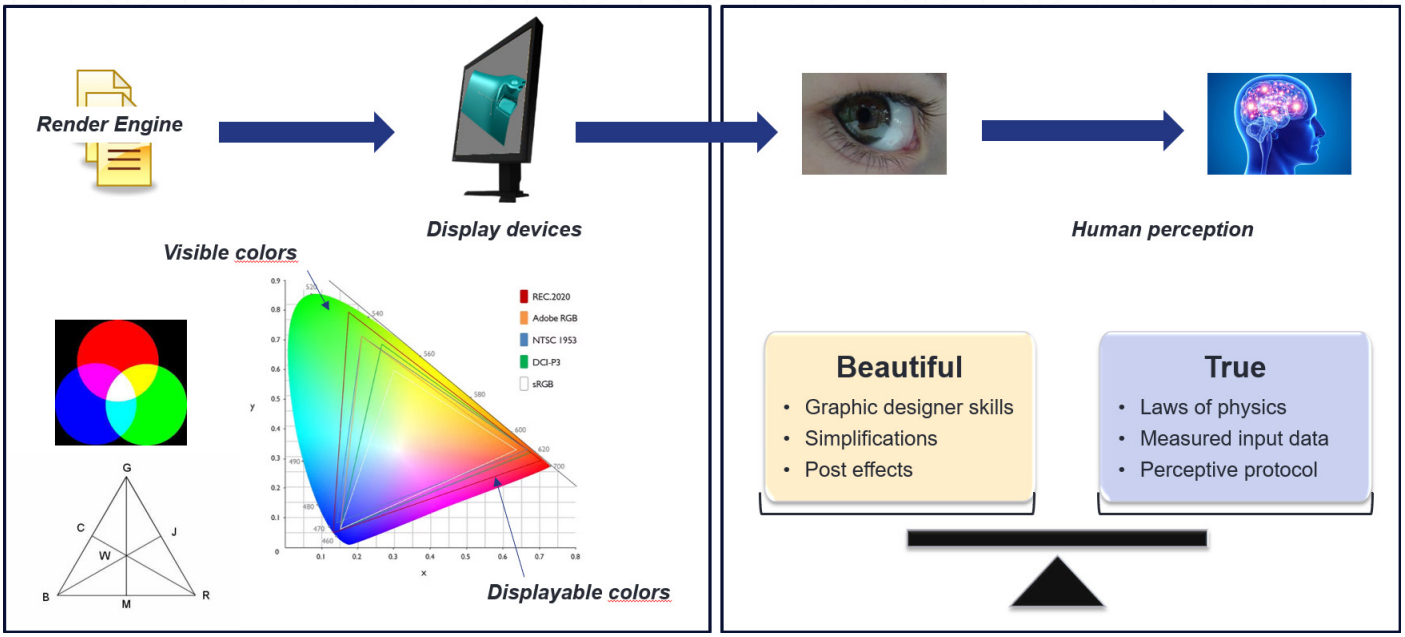


Fig. 9 Rendering versus perception, courtesy of Stellantis.

Another critical limitation lies in the human eye's sensitivity to luminance (see Fig. 10), which cannot be fully replicated by conventional display technologies. The human visual system can adapt to an enormous dynamic range – from bright sunlight to dim moonlight – while most screens operate within a much narrower range. As a result, scenes that involve intense highlights or deep shadows often appear compressed or unrealistic on standard displays.

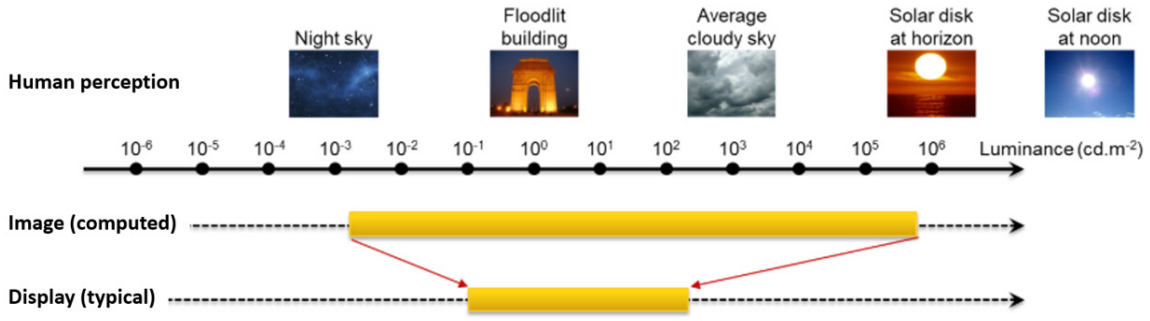


Fig. 10 Sensitivity to luminance versus image and display dynamic range, courtesy of Renault Group.

To address these challenges, there is a strong need for large colour gamuts and high dynamic range (HDR) capabilities in modern display devices. A wide gamut ensures that saturated colours and subtle hues are accurately represented, while HDR allows for a more faithful reproduction of brightness variations, preserving detail in both highlights and shadows. However, these advanced features only deliver their full potential when displays are carefully calibrated, ensuring consistency between simulated data and visual output.

Ultimately, even with HDR and wide-gamut screens, the gap between simulation and perception cannot be completely closed. Yet, these technologies significantly improve realism, making immersive experiences such as virtual reality and high-fidelity visualisation far more convincing.

These technical and perceptual considerations can have varying impacts on the user experience depending on the intended goal. When the primary objective is physical accuracy (as in the case of engineers and technicians), it is essential to establish strict and repeatable observation protocols to minimise external disturbances. Conversely, when aesthetic quality is the focus (such as designers or marketing teams), visual enhancements can be applied after computation through post-processing techniques, filters, and similar methods.

2.5.4 Introducing virtual reality and real-time graphics

Virtual reality aims to provide an immersive experience to the user, proposing a perception of the product at scale 1:1, with an intuitive and natural observation and interaction. In essence, to provide such an experience, virtual reality requires an update of the image calculated at a high frequency, of the order of 30 to 60 images per second for example, to ensure the interactive and immersive experience (see Figs 11 and 12). It also generally involves several "viewports", to display the corresponding field of view, and to generate the stereoscopy, necessary to contribute to an immersive perception.



Fig. 11 *Renault's CAVE (Cave Automatic Virtual Environment), an immersive room-scale virtual reality system, courtesy of Renault Group.*

As noted earlier, virtual reality typically uses OpenGL type technologies and real time rasterisation. Material modelling remains simplified, although recent GPU advances increasingly support Physically Based Rendering (PBR) models that better approximate light–material interaction.

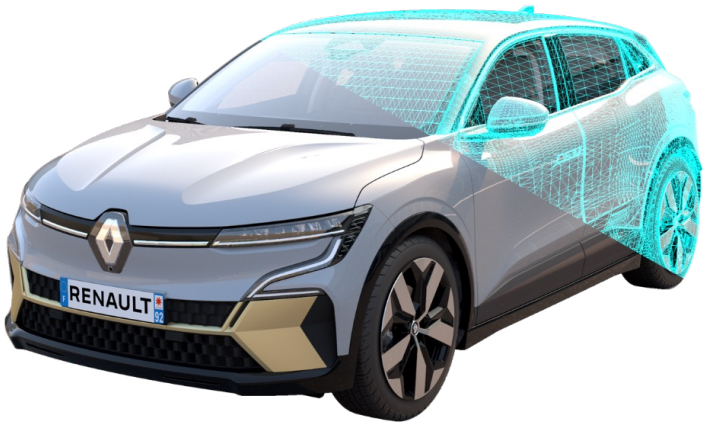


***Fig. 12** Virtual Reality – real-time graphics computing, courtesy of Renault Group.*

It is the same for light source models and the consideration of environmental light emissions, or the calculation of shadows, which also benefits from models calculable in real time increasingly accurate and realistic.

What is important to remember is that real-time graphics engines can calculate the image of a scene at about 60 frames per second, but that this speed of calculation can be detrimental to the accuracy of the photometric model. The result obtained is therefore beautiful, or photorealistic, but in no case is it true or physically correct.

2.5.5 Introducing visual simulation calculation

Visual simulation is a relatively recent branch of numerical simulation that aims to reproduce the physics of light – based on electromagnetic radiation, only a portion of which is perceptible to the human eye. Its objective is to quantify the exchange of energy between objects to determine their visual appearance.

In optical science, and especially in computer graphics, it is more appropriate to work with quantities expressed in visual photometry, such as lumens, lux, or candela per square meter (cd/m^2), which correspond to how humans perceive light.

The numerical models of graphics calculation are not the same as those used for virtual reality, previously described.

In a physical world, described by a "scene", all objects and light sources emit or reflect energy in the form of electromagnetic radiation. The objects are thus coloured, visible, and likely to illuminate the other objects of the scene, by successive reflections, refraction, and diffusion.

The algorithms of the global illumination rendering engine family use models that reproduce this principle of energy transfer, and work with models that on the one hand reproduce the rays emitted by a light source, and on the other hand the interactions of these rays with the surfaces of the objects encountered, via reflectance or transmission models, and this by successive iterations of transmission of energy from one surface to another.

Thus, after a very large number of successive re-emissions of objects on each other, an energy equilibrium is formed within the scene, and each object in the scene is then affected by a coloured light component. It is this colour that is viewable.

The image below in Fig. 13 represents the result of such a calculation compared with a photograph of a real vehicle in the same lighting condition.



***Fig. 13** Visual simulation (left) – Photo (right), courtesy of Renault Group.*

It is visible that these two images are close enough to each other, such that it is possible to study the vehicle and make decisions from its digital model, augmented with materials and calculated in visual simulation (Fig. 14), long before having a real vehicle available for testing.

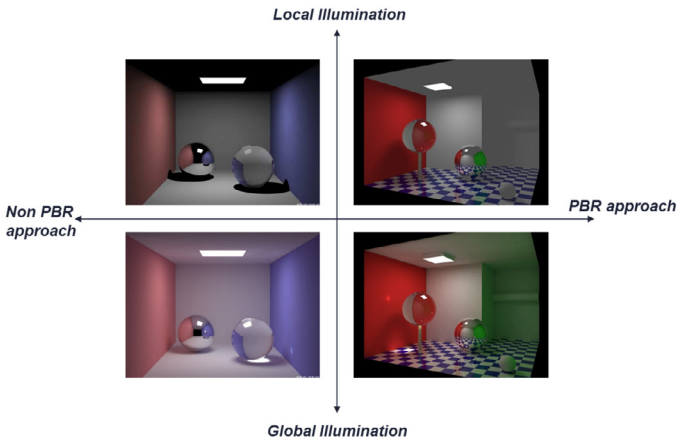


***Fig. 14** Impact of light physics modelling on rendering.*

Chapter 3: XR technologies - state of the art and next-generation

3.1 XR devices

Vision, touch, and hearing are the three primary human senses that XR technologies must stimulate to ensure user immersion. This chapter provides an overview of the technologies required to achieve this, apart from hearing, as it relies on well-established and conventional audio playback solutions.

3.1.1 Typologies of visual XR devices

In Virtual Reality, three main categories of devices enable immersive experiences from a visual standpoint (see Fig. 15). They operate through rendering engines.

- **Autostereoscopic screens** provide depth perception on a small scale, without the need for 3D glasses, offering a shared viewing experience.
- **3D screens or projectors** for big screens and large-scale tracked image walls, such as Powerwalls or CAVE systems. They create collaborative environments where users can interact with virtual content at room scale.
- **VR headsets** deliver full immersion by isolating the user from the real world and rendering a personalised first-person perspective.

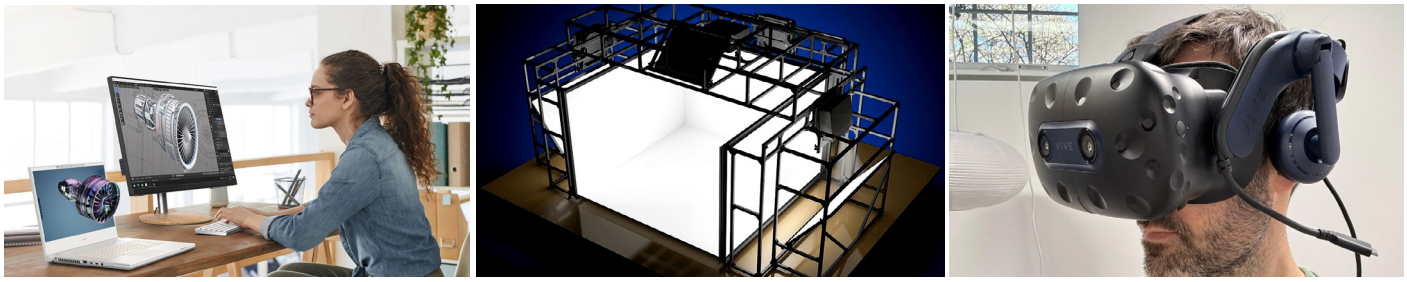


***Fig. 15** Autostereoscopic screen / CAVE system / VR Headset.*

For AR and MR, three main display technologies can be distinguished:

- **Projective Augmented Reality:** digital information is projected directly onto a recognised physical object.
- **Screen-based Mixed or Augmented Reality:** digital information is superimposed on a recognised physical object and viewed through a removable screen.
- **Immersive Mixed or Augmented Reality:** digital information is overlaid within the recognised physical environment and observed through a headset or smart glasses.

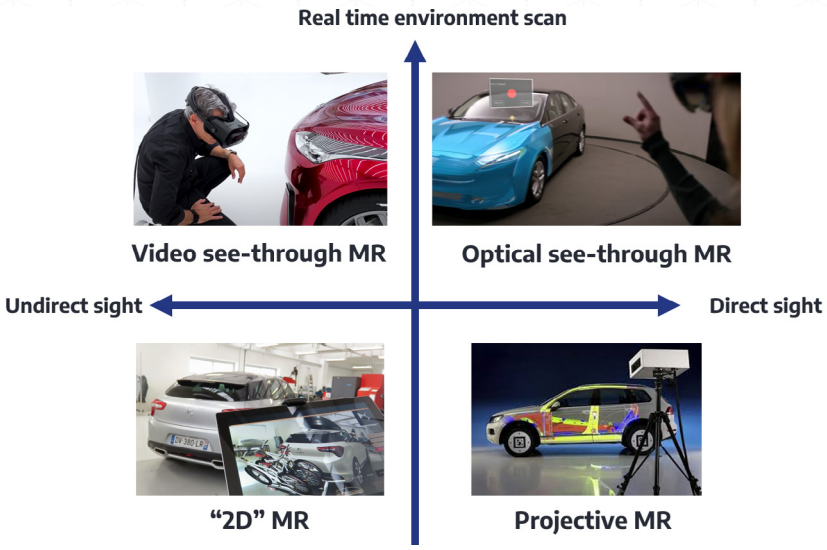


Fig. 16 Courtesy of Stellantis.

For immersive Mixed or Augmented Reality, two kinds of devices are available:

- **Optical See-Through (OST):** users look directly at the real world through transparent lenses that display virtual elements.



Examples: Oakley Meta Vanguard, Xreal Air 2 ultra, Ray-Ban Meta Gen 2, Microsoft HoloLens (V1 & V2)

OST-based MR glasses offer several strategic advantages for the consumer market that make OST devices suitable for everyday use and "light" AR applications:

- No need to process and recombine video streams with digital overlays.
- Customisable lenses adapted to the user's vision, improving comfort and usability.
- Less intrusive and closer to traditional eyewear, opening opportunities in fashion and luxury segments.
- **Video See-Through (VST):** also called Pass-Through, where cameras capture the real world and merge it with virtual content.



Examples: Pico 4, Apple Vision Pro, Meta Quest 3

In professional environments, VST headsets offer specific features:

- Efficient control of occlusion for accurate spatial alignment in industrial environments.
- High visual realism for complex tasks thanks to full-colour, high-resolution video overlays and visualisation of the user's body.
- Form factor that can embed powerful processors and sensors, enabling advanced features and connectivity.

3.1.2 Visual XR devices currently available

Table 1 below provides a concise overview of several mainstream VR and MR headsets, spanning both professional-grade and consumer-focused devices.

Features	Meta Quest 3	Apple Vision Pro	Samsung Galaxy XR	HTC Vive XR Elite	Varjo XR-4
Release Date	Oct 2023	Oct 2025	Oct 2025 (EU: 2026)	2023	Nov 2023
Price	~$499	~$4,200	~$1,799	$799–$999	$3,990+
Resolution (per eye)	2064 × 2208 px	3660 × 3200 px	3552 × 3840 px	1920 × 1920 px	3840 × 3744 px
Field of View (FOV)	~104° H × 96° V	~100° (approx.)	109° H × 100° V	110° diagonal	120° H × 105° V
Eye Tracking	No	Yes	Yes	No	Yes (200 Hz)
Face Tracking	No	Yes	Yes	No	Yes
Display Type	LCD + Pancake lenses	Micro-OLED	Micro-OLED	LCD + Pancake lenses	Mini-LED
Refresh Rate	Up to 120 Hz	90–120 Hz	72–90 Hz	90 Hz	90 Hz
Processor	Snapdragon XR2 Gen 2	Apple M5 + R1	Snapdragon XR2+ Gen 2	Snapdragon XR2	PC-powered (GPU dependent)
Weight	~515 g	750–800 g + external battery	545 g + battery pack	625 g (with cradle)	~1021 g (full setup)
OS / Ecosystem	Horizon OS	visionOS	Android XR	Viveport / SteamVR	SteamVR / Varjo Base

The table compares five leading XR headsets, highlighting how their specifications and design choices position them for different use cases and market segments. Meta Quest 3 stands out as an affordable, lightweight, and consumer-friendly device, offering solid resolution and refresh rate performance thanks to the Snapdragon XR2 Gen 2. At the opposite end, Apple Vision Pro targets premium productivity and media experiences with its high-end micro-OLED displays, advanced eye and face tracking, and powerful M2/R1 processors – though at a significantly higher price and weight.

Samsung's Galaxy XR has been designed to balance performance, mobility, and mixed-reality capabilities. It delivers high-resolution micro-OLED screens, integrated eye and face tracking, and the latest Snapdragon XR2+ Gen 2 chipset, making it a strong contender in the upper-midrange tier. HTC's Vive XR Elite, meanwhile, focuses on portability and PC-optional flexibility. Its compact form factor and moderate price make it suitable for mobile VR, although it lacks more advanced tracking features.

At the professional end of the spectrum, the Varjo XR-4 offers the highest display fidelity, the widest field of view, and industry-grade tracking capabilities, including 200 Hz eye tracking and advanced facial capture. Its reliance on PC-level GPUs and its heavier build firmly position it for industrial, simulation, and enterprise-grade applications.

Across the lineup, differences in display technology, processing power, ergonomics, and ecosystem integration highlight the diverse priorities of each manufacturer –from mass-market accessibility to professional-grade realism.

3.1.3 The evolution of visual XR devices

MR is rapidly emerging as the most promising direction for next-generation XR devices. By blending digital content directly into the user's physical surroundings, MR enables simulations to be experienced in real-world context with a level of relevance and intuitiveness that fully virtual environments cannot match. This seamless fusion of real and virtual elements positions MR as a strong candidate to lead the future XR headset market.

Its strengths are already evident.

- **Native collaboration:** users can naturally see, hear, and interact with colleagues, maintaining eye contact and benefiting from shared spatial cues.
- **Native safety:** the physical environment remains visible at all times, ensuring awareness of obstacles, tools, and ongoing operations –an essential requirement across industrial workflows.

At the same time, the rise of embedded artificial intelligence is becoming a decisive accelerator for MR adoption. On-device AI enables real-time scene understanding, spatial mapping, gesture recognition, and contextual assistance, dramatically improving responsiveness, realism, and user comfort. AI also makes MR experiences more adaptive –able to analyse the environment, anticipate user intentions, and recommend actions based on operational data.

However, several major challenges still need to be addressed for large-scale enterprise deployment:

- **Visual quality:** achieving wide colour gamut, HDR rendering, high brightness, and optical clarity for indoor and outdoor usage.
- **Miniaturisation and ergonomics:** integrating sensors, depth cameras, compute units, batteries, and high-resolution displays into lightweight, comfortable, all-day wearable form factors.
- **Battery autonomy:** providing at least four hours of continuous operation while supporting advanced features such as AI-based spatial processing, real-time object detection, and secure connectivity.
- **Connectivity and compatibility:** ensuring seamless integration with ERP, PLM, and MES systems, as well as robust, low-latency wireless performance in demanding industrial radio environments.
- **Durability and certification:** meeting strict requirements for dust, shock, and water resistance, and achieving certification for industrial environments.
- **User interaction:** delivering reliable voice, gesture, and tactile inputs – even when users wear gloves or work in noisy areas – while leveraging AI to improve recognition accuracy and personalise interactions.
- **Security and privacy:** ensuring compliance with corporate data governance, GDPR, and other regulations, especially given the continuous capture and AI processing of visual and spatial information.
- **Regulatory standards:** validating ergonomic comfort, safety, and AI-assisted functionalities for professional use cases.

AI's impact goes beyond simple enhancement: it transforms how MR devices perceive the world, support the user, and connect to enterprise systems. Intelligent assistants can guide operators step by step, suggest optimal actions, detect anomalies, or automatically log tasks. Predictive models can adapt simulations or workflows in real time. Combined with MR's physical anchoring, this creates a new paradigm of context-aware augmented work, blending perception, simulation, and automation.

Mixed Reality, empowered by on-device and cloud AI, has the potential to reshape training, operations, maintenance, and collaboration across industries. Overcoming the remaining technological and industrial challenges will be key to unlocking its full transformative power.

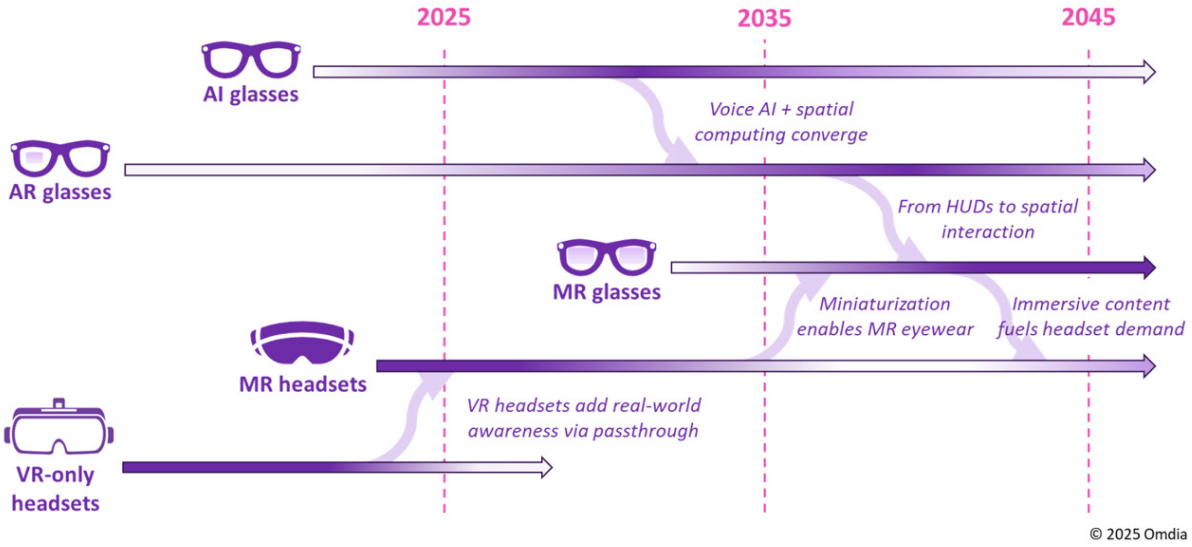


***Fig. 17** source Omdia: XR Market in 2035 and Beyond: Forecast, Challenges, and the Road to Mass Adoption.*

Fig. 17 illustrates XR device spectrum, a framework designed to map the evolution of head-worn devices across levels of immersion and real-world integration. Rather than treating XR as a single category, the model organises devices along a continuum that reflects both their intended use and the degree to which they immerse the user in digital content or overlay the physical environment with virtual elements.

At the fully immersive end of the spectrum sit VR-only headsets, which deliver enclosed virtual environments with minimal or no passthrough capability. These devices focus on presence and graphical fidelity but disconnect users from the physical world.

Moving toward mixed experiences, MR headsets use video passthrough to blend digital content onto the user's surroundings, enabling interaction with virtual and real elements simultaneously. Beyond these, MR glasses introduce transparent displays, allowing users to see the real world directly while still accessing AR overlays, with the optional ability to transition into full VR immersion.

Closer to the real-world end of the continuum are AR glasses, which provide lightweight heads-up information through minimal visual overlays. These devices prioritise contextual cues, navigation, messaging, and simple forms of interaction rather than deep immersion.

Finally, the spectrum includes AI glasses, which eliminate visual displays entirely. Instead, they rely on audio interfaces, sensors, and intelligent assistants to deliver hands-free utility, positioning them more as wearable computing companions than visual XR devices.

Presenting these five categories on a single spectrum clarifies how the XR landscape spans a wide range of form factors and use cases. It also underscores that the future of XR will not converge toward a single device type; rather, it will evolve across multiple paths driven by technological maturity, user needs, and the balance between immersion and real-world awareness. This framework sets out the foundation for understanding how adoption patterns may unfold in the coming decades.

3.1.4 Typologies of haptic XR devices

Haptic devices used in the automotive industry can be grouped into several major typologies, each addressing different levels of tactile fidelity and use-case specificity. They operate through physics engine management.

- **Vibrotactile systems** represent the most widespread category, relying on linear resonant actuators to provide alerts or tool vibrations. They can be embedded in gloves, controllers, or handheld tools. They provide lightweight and low-latency feedback.



Examples: Vive vibratory controller, Manus Prime 3

- **Force-feedback devices**, such as grounded robotic arms or exoskeletal gloves add a mechanical resistance that simulates object weight, shape, and rigidity. These systems are essential when precise manipulation of virtual components or realistic simulation of assembly constraints is required.



Examples: Haption Virtuose 6d, Senseglove Nova, Dexta Robotics Dexmo

3.1.5 What's coming next regarding haptic XR devices?

Although tactile surface-haptic devices are rapidly progressing, they are still not technologically mature enough for large-scale deployment. Studies show that users struggle with consistent shape and texture recognition under varying conditions (temperature, humidity, etc), underscoring the limits of today's friction-based rendering techniques. Despite these limitations, several emerging technologies point toward viable future solutions, including ultrasonic haptics, high-force piezo actuators, and hybrid lateral-force surfaces demonstrated. These innovations suggest that while tactile haptics are not yet ready for full industry adoption, the technological pathway to achieve this capability is increasingly well-defined.

3.2 Computer graphics hardware

To produce an XR experience, you need to generate computer graphics imagery. This can be summarised into two main approaches: rasterisation processing and offline rendering (see Fig. 18).

In the 1990s, we witnessed the emergence of the GPU for rasterisation. This hardware architecture was designed to handle geometric data represented by vertices, optimise their processing through primitive assembly, and interpolate information to compute the final pixels.

In contrast, offline rendering relied on algorithms running on general-purpose hardware without dedicated graphics acceleration. These algorithms read geometric information and computed pixel colours through interpolation, typically executed on a CPU (Central Processing Unit).

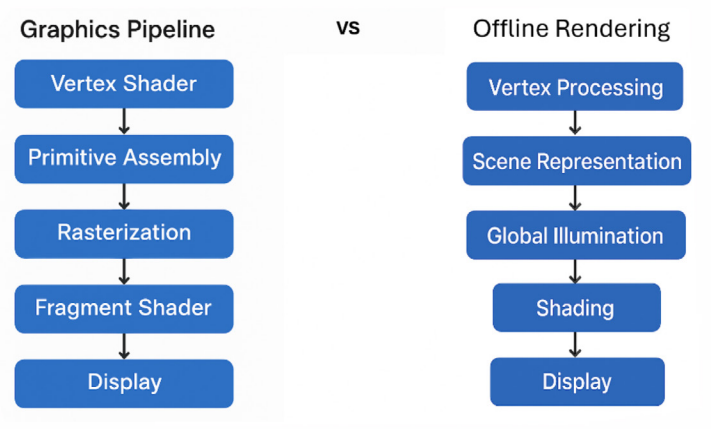


***Fig. 18** 1990's rasterisation versus offline rendering without post processing.*

The introduction of GPUs enabled real-time rendering, which was essential for XR use cases (see Fig. 19). By the late 1990s, programmable shading extended GPU capabilities, allowing more complex rendering effects such as realistic lighting, material interaction, and shadowing. This period also marked the first extended use cases of GPUs beyond graphics, known as GPGPU (General-Purpose computing on Graphics Processing Units).

In the 2000s, CAE simulations migrated to HPC (High-Performance Computing) architectures to reduce simulation time. HPC systems were primarily CPU-based clusters with high-end networking, memory, and storage. Offline rendering solutions also adopted these architectures to simulate complex optical phenomena and attempt near real-time performance.

By the late 2000s, GPUs evolved to support general-purpose computing through dedicated APIs like CUDA, enabling a hybrid approach that combined rasterisation and offline rendering techniques.

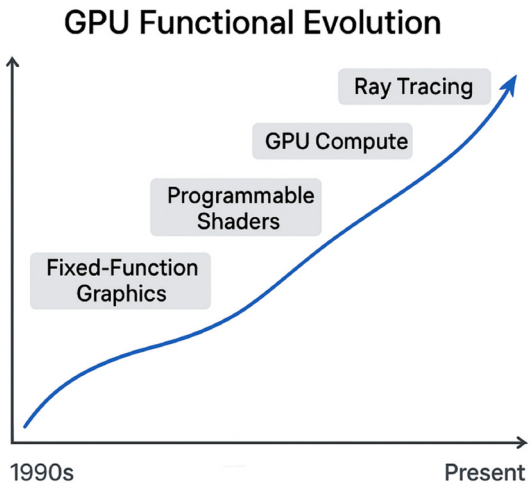


***Fig. 19** Evolution of GPU capabilities for the CGI pipeline.*

In parallel, XR use cases drove the development of advanced display systems such as CAVE environments, which required graphics clusters to manage synchronous stereoscopic rendering.

Network evolution introduced streaming solutions, opening real-time capabilities from HPC systems to remote displays.

The 2010s marked the standardisation of GPGPU and the beginning of AI training on GPUs.

At the same time, display technology advanced to HDR pipelines and extended colour depths (10-bit to 16-bit outputs), supported by new screens and GPU capabilities.

During this period, GPU performance significantly reduced the gap between rasterisation and offline rendering. More complex algorithms, such as ray tracing and global illumination, began to integrate into the rasterisation pipeline.

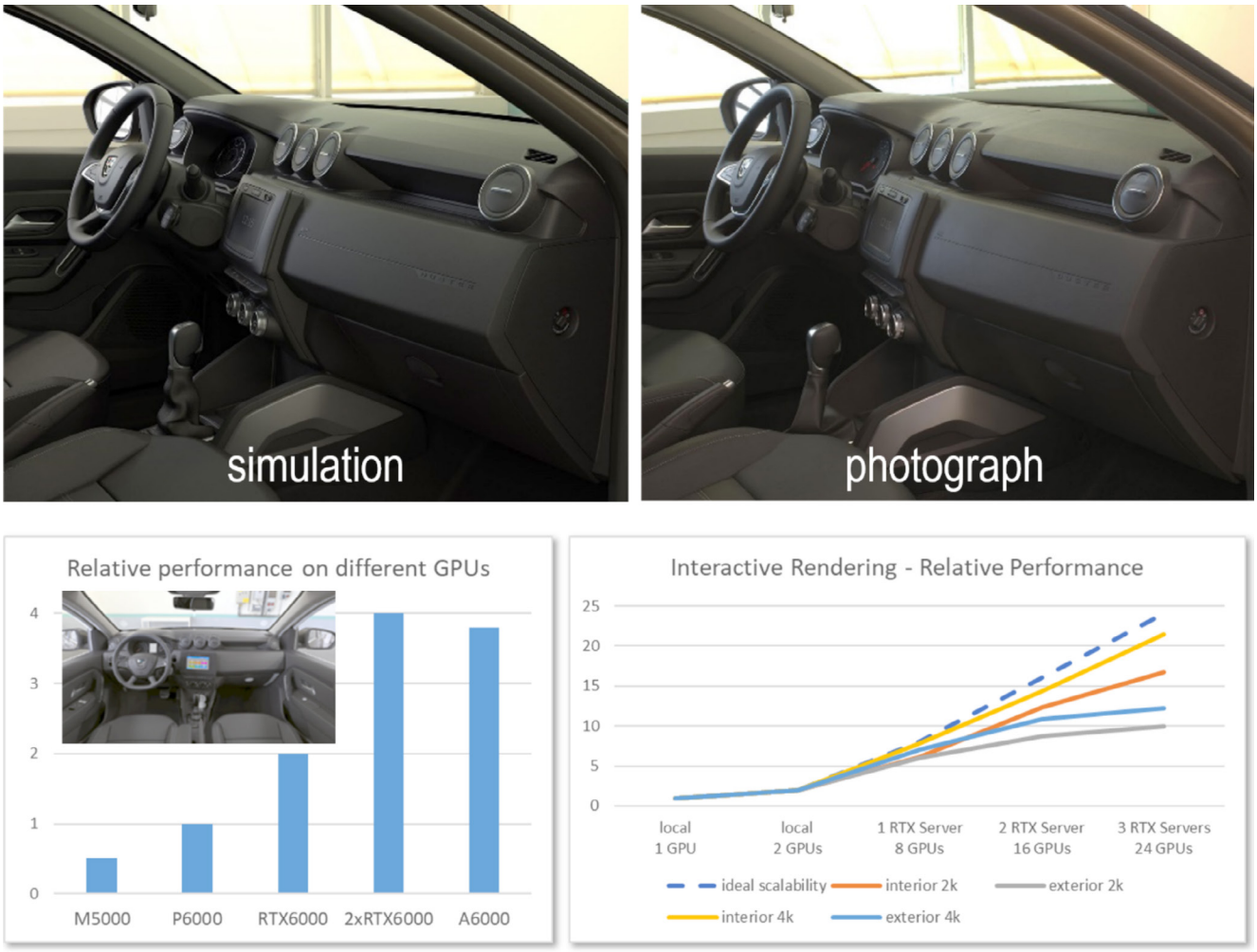


Fig. 20 *Example of study in 2020, to reach offline rendering quality in real-time with different HW architecture and illustrate GPU performance evolution, courtesy of Renault Group.*

Today, XR hardware is evolving toward cloud-based architectures and hardware-less solutions, where rendering is performed on remote GPU clusters and streamed to lightweight devices (see Fig. 20). This approach reduces local hardware requirements and enables high-fidelity XR experiences on portable headsets or thin clients.

In addition, AI-driven techniques – such as neural rendering, denoising, and upscaling – are increasingly used to accelerate computation and deliver more realistic results in real time. These methods optimise rendering pipelines by reducing the number of samples needed for global illumination or ray tracing, while maintaining visual quality. Combined with edge computing and high-bandwidth networks, these innovations are shaping the next generation of XR experiences, blending cloud rendering, AI acceleration, and immersive display technologies.

3.3. 3D Data

3.3.1 CAD geometry

3.3.1.1 History of 3D asset representation

Due to computer graphics workflow and GPUs, 3D assets are managed by triangular representation. The minimum description is based on 3D vector coordinates as supported by the STL format file. The STL format file was designed in 1987 by 3D Systems for usage in additive conception, 3D printing, and 3D Scanning. The mesh representation is interpolated from 3D points by the software to display it. The result can vary between software tools because each one may generate or modify shading data (such as colour and surface normals) differently.

In the 1980s, file formats like WaveFront's Obj introduced features such as colour, normals, UV mapping, and textures for advanced rendering (see Fig. 21). A 3D scene could also include complex animations requiring multiple nodes with specific transformation matrices, such as setting a centre pivot for wheel rotation.

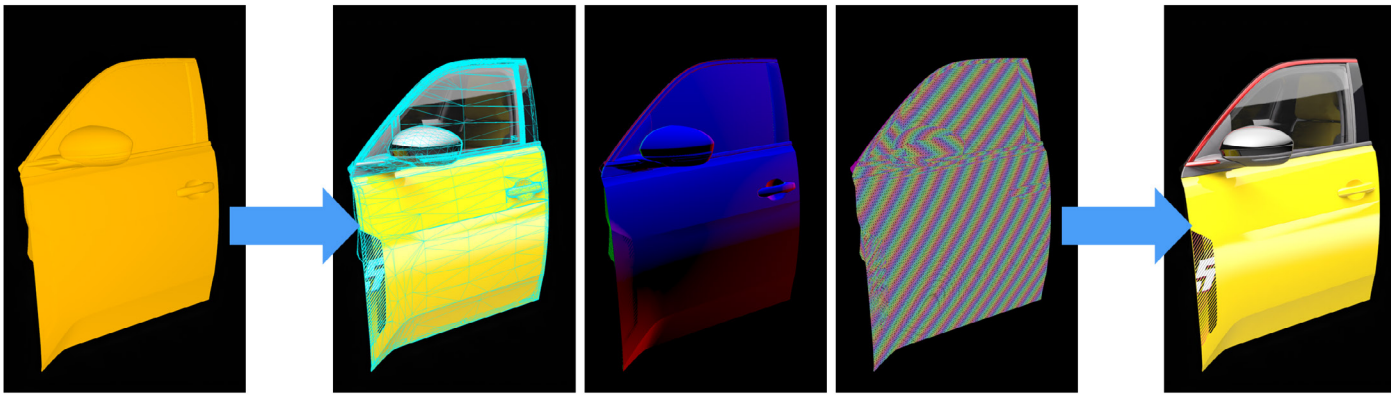


***Fig. 21** From nurbs to 3D asset based on triangle, normal and uvmapping.*

In 1996, the company Kaydara developed a format file FBX for their software FilmBox, in 2002 the software became MotionBuilder and used FBX as this official format file with the added value of handling ASCII and binary representation for large scene description, enriched material representation and complex animations. After the acquisition by Alias in 2004 and Autodesk in 2006, the usage of FBX increased outside the ecosystem of Autodesk. Although proprietary, it was very close to becoming a standard of exchange, with limited support for older versions due to its design.



***Fig. 22** From CAD to 3D scene with shading, configuration and animation, courtesy of Renault Group.*

Since the 2000's, the Physical Based Rendering approach has been introduced and has challenged format file to incorporate this type of material description. In parallel, industrial needs to exchange data with suppliers, partners and flexibility to reuse all data in a context of digital transformation have challenged certain digital players to propose standardisation.

One of the first to work in the direction of standardisation was Siemens, which published the description of its file format JT in 2007 and succeeded in standardising it by the ISO standard in 2012. Mainly focused on PLM data and CAD assets, the file format incorporates new concepts such as multi representation of 3D mesh with Level of Detail (LOD) and assembly concept with the PLMXML.

The automotive industry-led standardisation efforts saw Daimler support JT in 2010 during its PLM system migration. Industrial companies face the challenge of ensuring data usability across different PLM systems and software environments.

Since the JT standardisation and thanks to consortia such as Kronos Group we have seen new initiatives from the computer graphics eco-system such as the file format GLTF, published in 2015 and that supports PBR representation of material, since the V2, and is mainly designed for web usage.

3.3.1.2 The next step for CAD exchange and collaboration

During the 2000's, Pixar tried to improve the digital pipeline with these objectives:

- How to handle increasingly complex 3D scenes?
- How to optimise reuse of 3D assets and guarantee appearance?
- How to improve collaborative work between modeler, designer, animator and people in charge of the shading?
- How to manage different teams in different places?
- How to optimise lead time and provide parallel work on the same 3D scene?
- How to guarantee interoperability between their own software like RenderMan and Presto with software like Maya from Autodesk?

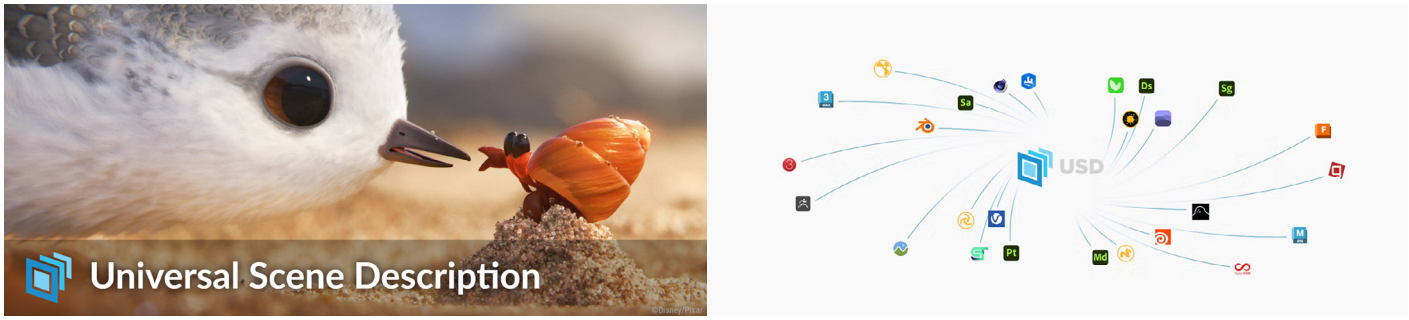


***Fig. 23** OpenUSD from Pixar to universal data exchange – illustrations form Pixar & NVidia.*

The result of its work was the file format USD, initially in-house and since 2016 as an opensource format called OpenUSD (see Fig. 23).

An interesting point in this approach is that OpenUSD was designed by key users. Also, the file format is scalable with backward compatibility by design.

Since its release as opensource, several major companies have been promoting OpenUSD, including Adobe, Autodesk and Nvidia. Recent communications from Autodesk and Siemens regarding OpenUSD confirm the success of this initiative, acknowledging that OpenUSD challenges established standards such as FBX and JT while also creating added value and new opportunities that encourage its integration.

3.3.1.3 Assembly approach and collaborative design

Assembly is used by digital solution to split PLM data from geometrical data or to provide the possibility of collaborative design.

In PLM system "catproduct" from Dassault CATIA or PLMXML from Siemens can be listed as an assembly file. For collaborative design "mb" file from Autodesk Maya or "csb" from Deltagen, illustrate how to work on the same 3D scene but with one user per subcomponent.

OpenUSD extends this approach to collaborative work on the same asset by splitting activity at parameter level such as material of a part, kinematic of multi part, and so on.

Assembly approach is also a prerequisite for the automatic update process as used in the VBOM approach introduced by Siemens, RTT and BMW in 2011. Assembly manages the overall 3D scene structure, position, metadata, ID and version of parts references. Based on this architecture, a partial update of the 3D scene can be managed, with the geometrical part the minimum level and stores as a single file linked to the assembly file.

OpenUSD has the same mechanism but is not limited to parts and 3D meshes. Different users can collaborate within a single 3D scene by focusing on distinct tasks: one may handle shading for specific components, another may edit the 3D mesh directly, while a third defines kinematics or animations. All modifications occur seamlessly within the same unified environment.

3.3.2 Digital materials

In order to accurately render 3D CAD models for high-end visualisation use cases, it is necessary to utilise shaders that were generated using scans of physical material samples. Without this scanning process, there would be no correlation between the physical and virtual world when it comes to attributes such as colour, grain or gloss. The engineer or artist must reference the physical sample in the real world and attempt to recreate the observed details using the visualisation software. This would lead to longer development timelines due to the need for numerous iterations based on variables such as lighting, monitor calibration or the creator's ability to perceive how light and colour interact with the sample.

It is typical that a visualisation software package comes with a default library of shader examples ranging from car paint to leather, however these generic examples are only useful for exploring ideas in the early stages of automotive design when the styling-theme surfaces are not mature and are constantly changing. When colour, material and finish (CMF) decisions need to be made in the development phase of the process, then the scanned material shaders are critical. More information on these use cases will be available in the CMF Visualisation portion of the paper.

The process of scanning material samples for use in high-end visualisation has evolved over the years, and it can highly depend on the visualisation software you intend to use. Automotive OEMs utilise many different visualisation software packages, due to specific features for 3D modelling, data preparation, animation, interaction, XR, or physically correct simulation capabilities. This leads to the need for multiple shader formats that can properly represent the vehicle across these software packages for different use cases. Further, it is important that the scanning and processing of physical materials is as agnostic as possible and not relegated to one specific software package.

Another obstacle automotive OEMs face is ensuring shader libraries are available across multiple engineers, designers, teams, facilities, and global regions. It is very typical for individuals to build and curate a personal shader library and resist company-wide standardisation due to artistic preferences. However, as new information is introduced regularly – ranging from minor adjustments to completely new colours – it is important to have "live" access to a "gold-source."

Here are a few key points to consider for maximising efficiency, accuracy, and utilisation:

Upfront requirements and expectations

Understanding the downstream visualisation software is critical for ensuring that materials are captured and processed correctly. Some software tools can utilise industry standard formats, while others may be lagging or have no plans to adopt new formats. Some simulation engines require specific attributes that need to be captured with proprietary scanning technology. There is no guarantee that numerical values for attributes like glossiness or transparency will be identical across software packages. It is important that users and decision-makers understand the accuracy limitations of 3D visualisation. Even with the best equipment, some complex materials may not appear as they do in real life, and physical prototypes will still be necessary to make critical final decisions before production.

Accurate capture

Material sample scanning and processing has greatly improved with the addition of new dedicated scanning devices and processing software over the past decade. Previously, the use of cameras and flatbed scanners

with photo-editing tools were predominately used. This means that materials were only being scanned from a single angle. Now, we have tools that can capture material attributes from multiple angles under different lighting conditions. As a result, the starting point for processing the capture into a shader has more information, including reflectance properties. Or, in the case of car paint, flop or metal flake parameters. In addition, the captured images are not constrained to 8-bit sRGB colour space, allowing for more accurate linear depth and range of colour. The processing software enables efficiency gains for breaking up the capture into multiple maps for colour, bump/normal, gloss, and more. When scanning grains, the software can help alleviate tiling issues (seams or repeating patterns). More recently, it has become a standard practice to generate shaders by procedurally borrowing a grain from one scan and a colour from another to conFig. an entirely new shader. These different attributes can be configured for new options without the need to scan 1:1 every sample for every combination, which saves significant time and reduces waste.

Validation process

Correlation between the real-world physical material sample and the virtual-world shader is critical to avoid downstream issues when the shader is used in visualisation reviews or marketing content. One inaccurate shader could damage the reputation and reliability of virtual tools in the eyes of decision-makers or potentially show a product to a customer that is not an accurate representation of the product being ordered. It is not possible to validate every real-world viewing scenario due to differences in how display technologies represent colours. However, it is important, at a minimum, to validate physical versus virtual in a controlled environment as a baseline. This controlled environment should not change as the library of shaders is developed over time, otherwise shaders that were previously validated for accuracy may not match the new shaders that utilise a different validation environment. This controlled validation environment consists of a set of different temperature lighting scenarios, including a lightbox with grey walls and floor. Colour-checking devices typically used in the film and photography industry are also beneficial for correlating the physical and virtual worlds. The high dynamic range 360 image (HDRI) used in the visualisation software is an exact match to the physical light box. This HDRI is utilised not only as the background for reflections on the virtual sample, but also to cast light in the virtual scene. The person validating the accuracy of the shader can directly compare the two with a calibrated monitor sitting directly next to the physical light box. Other lighting conditions, such as an outside patio setting with different sun and sky options, are also beneficial for a more natural representation that is familiar to decision-makers.

Sharing

Automotive OEMs need to store, maintain, and share multiple shader libraries for use in different software packages. Each software has its own method for connecting to libraries of assets like shaders. In addition, some materials may still be under development from the design team while others have been validated for use in marketing, which means that there may need to be access control limitations for security and proper use. Ideally, shaders would be created and uploaded to a centralised repository for use and maintenance. However, with the growing use of game engine technology in automotive visualisation, some software packages require shaders and other assets to be stored locally with the project with the intent to be packaged into a stand-alone application. In these cases, users may need to periodically download shader libraries or utilise third-party version control tools to manage updates. The key takeaway in all cases is that it is critical that all end-users of the library need to have access to the latest updates to reduce errors and rework as materials continue to develop.

Calibrated viewing

This is not just important during the validation process, but also downstream, as the shaders are utilised in design and marketing reviews. Having a dedicated space with a colour capable and calibrated monitor is critical for viewing the shaders accurately and making informed decisions on materials. Some specialised displays can produce a high-dynamic range realistic image with a wider colour gamut, higher brightness white levels and darker blacks that mimic real-life more closely to the human eye's perception. The review space should also minimise ambient lighting. It is typical in a design studio to have very bright daylight both natural and artificial around displays. This light and all the surrounding objects reflect off the screen, or diminish the brightness, making colours look washed out, too cool, or too warm. This can lead to misinformed decisions and unnecessary rework for creative teams.

All of these factors need to work in unison as a single ecosystem for the creation and use of shaders. If one aspect of this system fails along the way, it can have a negative impact on the whole outcome. However, if investments in skills, technology, and process standardisation are made and maintained, then consistency of accuracy and quality of output can be ensured.

3.3.3 Virtual environments

3.3.3.1 Definition

Virtual environments (VEs) (see Fig. 24) are computer-generated environments where users can interact in real time. These immersive spaces, accessible via XR devices, enable collaboration and communication between users and virtual objects, and persist independently of individual sessions.



***Fig. 24** Virtual worlds in video games: old Paris in Assassin's Creed / an island in Fortnite.*

In the automotive industry, VEs enable engineers and operators to interact with digital twins of products, factories, or processes in use conditions that approximate real life.

We can envisage several kinds of VEs:

- Fully artificial virtual world: often used in video games, serious games or marketing media
- Fully accurate reproduction of the real world: useful for specific landscapes or industrial settings when the accuracy is mandatory for the purpose of the simulation
- Mix of both: useful to test variants of existing life conditions (like a new installation on a workstation, or different lighting conditions, etc)

3.3.3.2 How virtual environments are created

To populate these VEs, several virtual objects can be combined through different formats:

- Geometrical objects and 3D models: generally, surfaces or volumes (CAD or mesh) for parts, or avatars
- 2D models: generally 360° pictures or point clouds to visualise the scene
- Light sources: mandatory conditions to see objects, colours, shades, ...
- Materials: textures or digital materials to allow interactions between light and materials
- Sounds: spatialised sound for immersive experiences, including environmental noise and voice communication.
- To power up these VEs
- User interaction layer: interfaces for controllers, hand tracking, voice commands, haptic feedback, and eye-tracking
- Logic: governs object behaviours and scenario for dynamic environments.

These VEs are directly perceived by human beings through their own senses, essentially sight, haptic, and hearing. Consequently, the main interaction modes with VEs must feed our senses to allow precise manipulation of 3D models, user's displacements, and realistic observations.

That's why creating these environments involves two main kinds of software to enable realistic interactions:

- Render engines provide real-time visualisation with photorealistic lighting and shading,
- Physics engines ensure accurate simulation of gravity, collisions, and material properties.

The current frontier combines spectral rendering, physics-based simulation, and AI-driven content generation to achieve natural perception and dynamic adaptability. These advances position virtual environments as a cornerstone for Industry 4.0, bridging design, production, and maintenance through immersive, data-rich experiences.

3.3.3.3 3D environments – the AI disruption

The use of virtual worlds is gaining significant momentum in our industry. Until recently, virtual worlds were primarily used for immersion purposes in our XR simulations. Achieving a high degree of visual and physical realism is an important task to ensure quality immersion, but it is very time-consuming. This challenge is likely one of the reasons behind the difficulties in deploying XR technologies.

With the advent of AI, the task of creating virtual worlds have become simpler, faster, and more efficient, enabling the rapid creation of immersive content.

At the same time, the learning needs of AI for autonomous vehicles or industrial robotics are critical for safety and regulatory reasons: these systems must be trained in a huge number of life scenarios, some of which are very dangerous or extremely rare in the physical world.

Consequently, virtual worlds appear to be the only way to address these issues. Beyond simulation scenarios, they must not only be representative of the real world but also reflect its variability (lighting conditions, weather, materials, etc.). Only AI-based technologies can meet the challenge of creating virtual worlds within controlled time and cost constraints.

Traditional creation methods include HDRI capture, which produces highly realistic environments but requires heavy models and long lead times – ideal for showcasing vehicles in lifelike settings. Another approach is 3D modelling and point cloud techniques, which also deliver precise and realistic spaces suitable for immersive navigation. But these methods don't fit the time and cost constraints.

Generative AI methods, such as 3D Gaussian Splatting, are transforming virtual world creation. These techniques allow for rapid and lightweight reconstruction of environments from real-world captures (a few pictures), generating immersive and realistic 3D models that are VR-ready. This innovation makes it easier to create synthetic worlds and supports more accessible, scalable immersive experiences. The convergence of classic and generative methods expands XR applications, providing tailored environments for simulation, training, and industrial collaboration.

Chapter 4: The business case for XR

4.1 Applications in automotive

In the automotive industry, XR plays a pivotal role across multiple domains, ranging from early design styling to advanced marketing strategies. These visual assets can vary significantly in purpose and precision – from highly polished beauty shots that leverage artistic lighting to create an emotional connection with the product, to rigorous visual simulations used for engineering validation. The spectrum of applications spans simple 2D renderings to fully immersive, interactive reviews in virtual environments, enabling stakeholders to experience and evaluate vehicles before a single physical prototype exists.

This chapter explores how immersive technologies, such as VR, AR, and MR, are revolutionising automotive workflows. We will examine their impact on design processes, collaborative engineering, cost optimisation, and customer experience evaluation, highlighting how these tools bridge the gap between conceptual visualisation and functional validation.

4.1.1 Use-case: Lighting simulation

The aim of lighting simulation is to anticipate issues to deliver contractual design and to reduce the number of physical mock-ups during the design phase. Lighting systems are becoming increasingly complex and simulating the path of light from the emitter to the outside of the optical stack requires a great definition and knowledge of the system. This type of use case is based on 2D image evaluation due to the cost impact on HPC utilisation and need for high-end displays.

Current display technology capabilities are limited; therefore, a false colour post-processing visualisation approach is used to produce objective evaluation with luminance view for homogeneity check, illuminance view for light leak detection and technical evaluation (see Fig. 25).

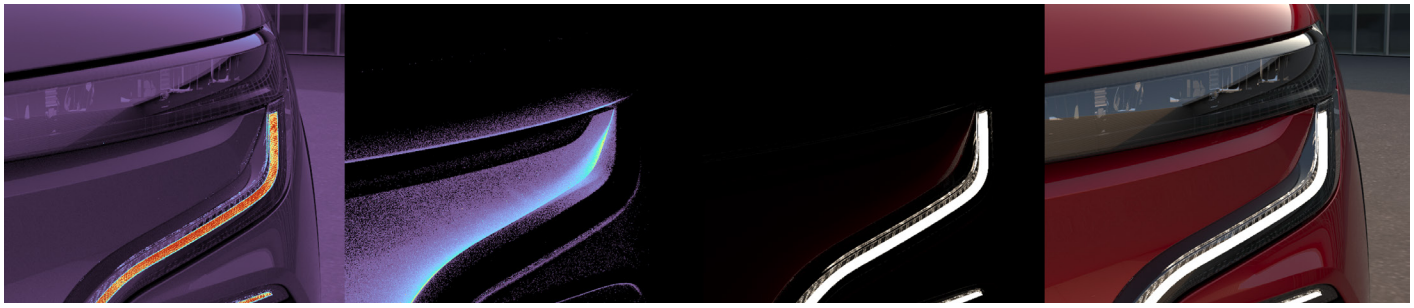


***Fig. 25** Objective evaluation for homogeneity, leak of light analysis, design validation, courtesy of Renault Group.*

Beyond this objective approach, subjective evaluation of lighting simulation is utilised (see Fig. 26). Subjective evaluation illustrates whether the design meets the specifications of the styling department's requirements

in the initial phase before the physical prototype or between two physical prototyping loops. The main challenge is how to reproduce in the simulation the dynamics of the physical luminance or the physiological effect due to this luminance such as glare around the sources. For this, we combine a high luminance display (1000 cd/m^2) and a post-processing algorithm to emulate the glare effect.

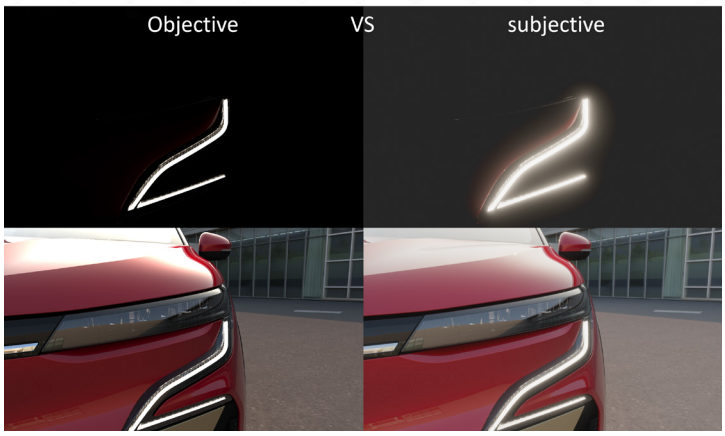


***Fig. 26** Objective evaluation VS subjective evaluation with eye physiology-based post processing, courtesy of Renault Group.*

This combination allows us to give the styling department a realistic idea of how the concept is perceived using physics-based constraints. For example, the perceived size of a lit object at different distances and if the design is still readable. This approach allows the engineering department to be more confident in technical choices in upstream phases.

During project development, simulation allows us to check the mock-up before the first part is manufactured and to make technical and Perceived Quality feedback enabling early corrections or deep analysis of complex optical phenomenon. This allows time savings on the project as problems are caught earlier, reducing rework development iterations and issues later in the process.

This simulation offers compatibility with the virtual twin. Lighting details can be seen and evaluated on the full vehicle. This presents the advantage to be able to catch problems that a partial mock-up cannot detect.

4.1.2 Use-case: Perceived quality review

The purpose of these reviews is to identify visible defects, assess their severity, and decide on corrective actions. In the early stages of design, such reviews are conducted digitally using real-time rendering simulation techniques.

The process begins with an exploration of the car's 3D model to pinpoint areas likely to cause defects. These areas are then examined in virtual reality through immersive simulations, enabling observation from natural human viewpoints and movements. This requires extremely high software and hardware performance due to rendering precision, user motion, and real-time computation at frequencies exceeding 60 Hz.

Often, these reviews involve multiple users collaborating on the same model, sometimes from different locations and devices.

Model realism depends on the accuracy of light simulation on materials, making precise shader creation a top priority. Physically Based Rendering (PBR) achieves this by using measured optical properties of materials, combined with accurate light source modelling.

However, human perception introduces additional complexity. It involves hardware factors (colour gamut, lenses, resolution, contrast) and physiological and psychological aspects of vision. For instance, image exposure must account for the eye's ability to adjust pupil size in extreme lighting conditions (see Fig. 27). Tone mapping techniques are therefore essential to prevent over- or underexposure.



***Fig. 27** Steering wheel zone overexposed due to underexposure of passenger footwell, courtesy of Stellantis.*

This perceived quality use-case combines the most demanding requirements: highly detailed models, complex optical simulations, real-time rendering, and perceptual constraints. The stakes are high, as this approach significantly reduces cost and time compared to physical mock-ups and strongly influences customer perception and brand image.

4.1.3 Manufacturing simulation

Immersing operators in a virtual workstation is an effective approach for assessing the performance of manual assembly processes. The primary objective of these simulations is to identify any factors that could hinder vehicle assembly and optimise workstation design accordingly.

Two main categories of issues are analysed:

- Technical feasibility: collisions or complex trajectories caused by spatial constraints (parts, tools, or workstation environment).
- Human feasibility: ergonomic challenges such as posture, effort, visibility, accessibility, safety, and work pace.

Workstation optimisation depends on multiple factors, including layout (line-side furniture, working height), tooling and part handling (weight, cognitive load), task balancing, and human behaviour.

Beyond conventional VR techniques, these simulations require a high-performance physics engine to compute real-time collisions, contact and friction forces, and even part deformation (e.g., cables). Incorporating haptic feedback can further enhance realism and accuracy (see Fig. 28).

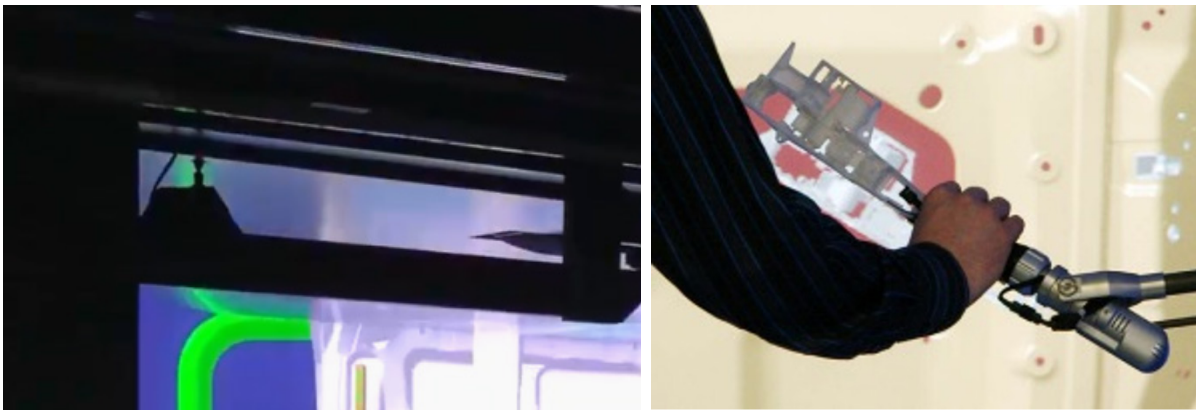


***Fig. 28** Assembly process simulation with haptic feedback, courtesy of Stellantis.*

4.1.4 Use-case: Colour, Material and Finish (CMF) visualisation

It is necessary for automotive OEMs to find opportunities to reduce time and environmental waste in the vehicle development process. Vehicles are complex and time consuming to design. Many considerations regarding CMF need to be measured and balanced across safety, sustainability, aesthetics, supply chain, durability, and cost.

Traditionally, it was necessary to utilise physical prototypes and prints to make every CMF design decision. For exterior paint or finish, physical examples could range from panels, scale models, components, wheels, full-size models, or real vehicles. For interiors, the effort and cost are multiplied when building partial or full bucks (interior prototypes) for CMF validation. In many cases, these interior bucks are indistinguishable from a real interior, allowing designers and leaders to make well-informed decisions relatively early in the process.

With the advent of high-end visualisation and immersive technology, it is no longer necessary to rely solely on physical prototypes to make CMF design decisions. This technology is not only utilised by designers and engineers in the development process, it's also used by the customer when they configure a vehicle on a website.

Today, automotive OEMs can replace many physical prototypes with virtual reviews. These virtual reviews can be supplemented with physical samples of materials created by suppliers or in-house fabrication shops. These samples are critical for connecting what the reviewer sees virtually on the display with the

real-world representation of the material. Current virtual tools are still unable to replicate the full spectrum of the human-eye's perception of colour, or the tactile feeling of the material grains and finishes to understand perceived quality.

In many cases, it is experientially beneficial to replicate the human body position in the vehicle environment, either by having the reviewer stand away from vehicle exterior or by mixing physical interior seating bucks with virtual- or augmented-reality head mounted displays and controls. By putting the reviewer into a natural seating position, the reviewer can view the interior from the customer's realistic perspective and not focus on details that may be hidden in the real product. These physical seating bucks can be very crude and easy to make or be more sophisticated and reconfigurable depending on the need of the design studio.

Examples of CMF visualisation use cases include:

- Visualisation of CMF on new design theme surfaces
  - Reviewing new paint proposal on vehicle concept as it's still being iterated prior to a physical prototype model
- Ideation on placement of CMF on vehicle
  - Mid-cycle update on vehicle interior, arranging different ideas on where to place new decorative trim or colour options
- Validation of placement of CMF on vehicle
  - Product correct documentation for manufacturing and marketing of all possible configurations
    Veiling and glare for outward visibility
  - Instrument panel reflecting on windshield or infotainment display reflecting in driver-side window

As high-end visualisation and immersive technologies continue to mature, it is expected that virtual reviews will continue to replace physical prototypes in the development process. However, currently there are no technologies that can provide decision-makers with 100% certainty that what they are seeing virtually will manifest the same way physically in the product. Therefore, some physical prototypes, especially in the latter stages of the process, will remain a critical aspect of vehicle design and development for the foreseeable future.

4.1.5 Use-case: Aerodynamics development using virtual reality

Aerodynamics has emerged as a critical area of focus for all automotive manufacturers, especially given its substantial influence on the range of electric vehicles – contributing an estimated 30-40% to overall driving range. This importance has driven a transformation in the aerodynamics development process, moving away from traditional wind tunnel development testing toward advanced virtual tools.

Historically, aerodynamicists and designers would collaborate in wind tunnels, making real-time modifications to vehicle exteriors to achieve optimal drag coefficients while maintaining the intended styling. This hands-on approach, while effective, was limited by physical constraints and required all stakeholders to be present at the same location.

Today, leveraging high-fidelity virtual aerodynamic development tools that enable detailed simulation and visualisation of airflow around vehicles from concept through production. These tools provide unlimited flow visualisation, allowing engineers to observe and diagnose aerodynamic phenomena that would be

impossible to see in physical tests. The shift to virtual methods not only streamlines the process but also opens new avenues for collaboration.

A key innovation in this space is the integration of VR into the aerodynamic development workflow. VR addresses several challenges inherent in traditional and even 2D digital approaches:

- Deeper Understanding: Immersive VR environments allow users to experience aerodynamic results in three dimensions, revealing insights and flow behaviours that might be missed in 2D visualisations.
- Enhanced Visualisation: Complex unsteady and underbody flow features are more intuitively understood in VR than when examining physical models or flat screens.
- Remote Collaboration: VR enables real-time, interactive collaboration among engineers and designers located in different regions, supporting multiplayer sessions where participants can jointly analyse and modify vehicle surfaces.
- Interactive Experience: The hands-on, interactive nature of VR fosters a more engaging and productive environment for decision-making, as teams can manipulate models and instantly see the effects of proposed changes.

By embracing VR in combination with other virtual tools, we are not only improving the efficiency of aerodynamic development but also fostering a culture of innovation and cross-functional teamwork that is essential for the future of mobility.

During a VR review (see Fig. 29), engineers and designers can visually assess the aerodynamic performance of a vehicle model. The immersive environment makes it easier to intuitively understand how and why airflow behaves in certain ways, helping teams identify exactly where surface modifications are needed to reduce stagnation pressure and eliminate unwanted wakes.

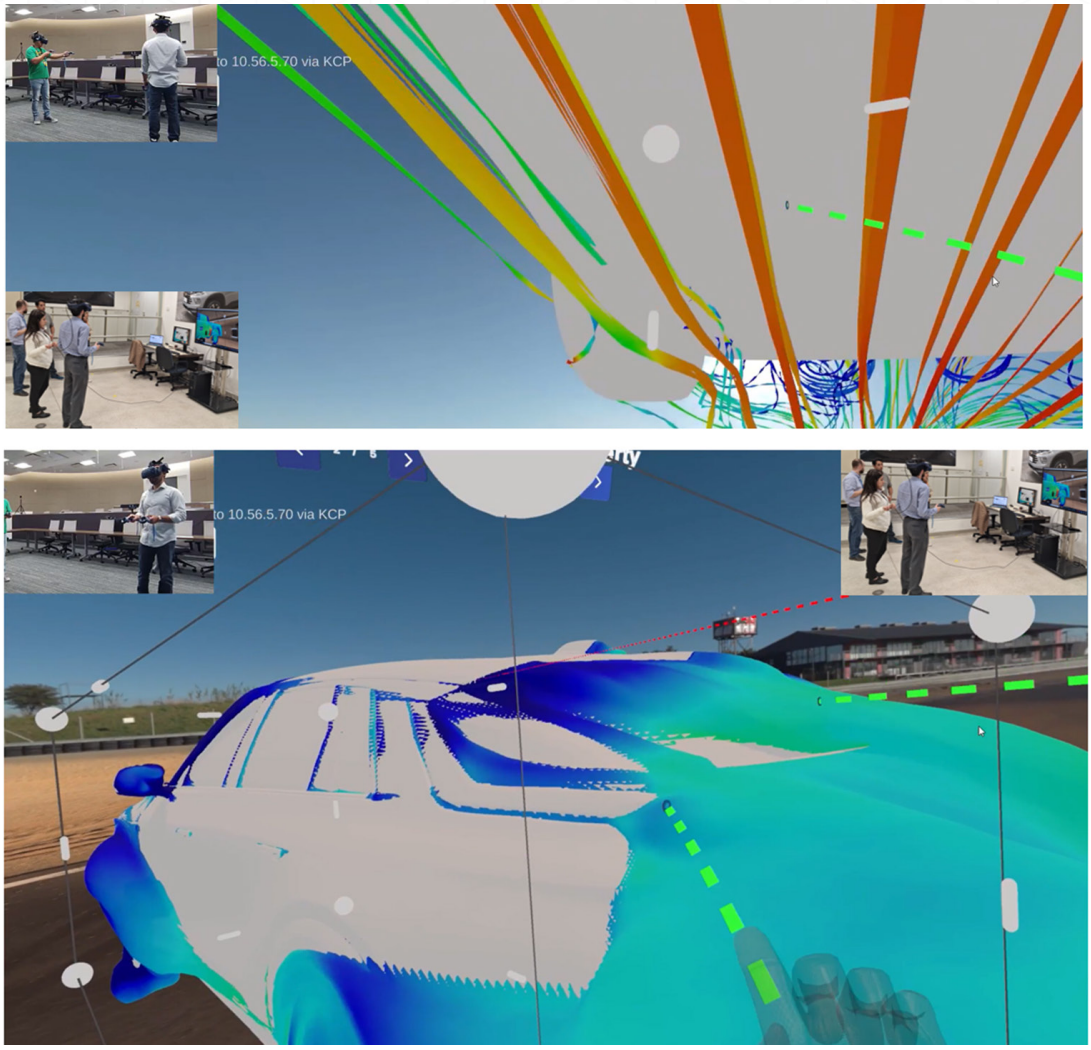


***Fig. 29** Real-time collaborative review of aerodynamic simulation in different locations, courtesy of General Motors.*

Virtual reality allows users to immerse themselves in complex flow field insights, optimising aerodynamic performance. It enables multiple users to review the same results in real-time, regardless of their physical location. In this interactive environment, individuals can engage with the data and point out specific areas of interest, enhancing teamwork and understanding while facilitating real-time interaction from anywhere in the world.

The technology enables other users to follow the perspective of a lead user within the virtual reality environment (see Fig. 30), enhancing communication during reviews and easing the learning curve for those who are not familiar with VR navigation.

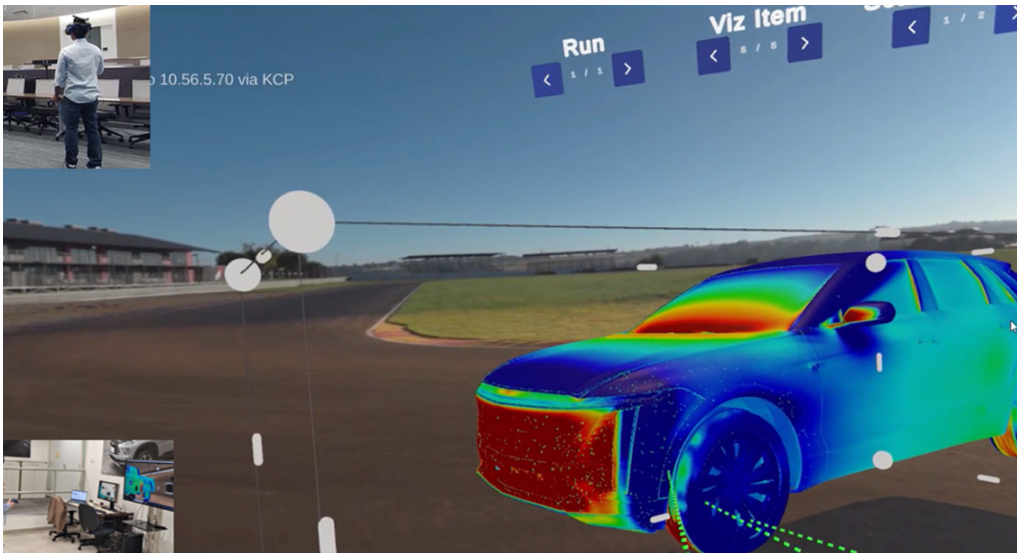


***Fig. 30** Easy identification of areas of improvements by using virtual reality, courtesy of General Motors.*

4.1.6 Use-case: Powertrain CAE virtual reality review

Powertrain engineering development has shifted significantly to virtual optimisation and validation recently, powered by computer-aided engineering (CAE) tools such as computational fluid dynamics (CFD). One example is using CFD to simulate coolant velocity and heat transfer in the cooling jacket of an internal combustion engine. The purpose of such a cooling jacket is to keep the engine metal components cool, preventing parts from failing due to thermal stress or fatigue.

Historically, development of these cooling systems includes making geometry changes to parts, targeting flow balance or velocity. Then, manufacturing the prototype parts and physical test validation would be required to ensure the resulting temperature of the material does not lead to failure. This test result is separated by multiple physics regimes from the flow field.

Creating a CFD model of this cooling jacket allows direct observation of the geometry impacts on flow. A CFD model will include physics-based calculations of the entire cooling jacket. Inside such a model, the velocity and pressure values are calculated everywhere, which provides the opportunity to interrogate the model to understand the flow. In this step, the CFD analyst creates flow streamlines, section planes of the velocity field or surface contour plots of the pressure field – to ensure that performance targets are met or designs can be optimised to reduce cost.

Virtual reality bridges the gap between these high-fidelity CFD results and the CAD designers, allowing them to immerse themselves into the flow domain and experience how the fluid behaves. Features provided by virtual reality review of CFD results include:

- Visualising results
  - Walls – surface contours
  - Volume – coloured fog or smoke effect
- Inserting flow particles and observing their motion
- Dynamically cut section planes through flow fields
- Creating surfaces of constant velocity or pressure to visualise wakes
- Sharing the virtual reality session for further collaboration

These features generate a strong intuition for the geometry impacts on flow. This intuition, coupled with the ability to modify the 3D CAD models, directly empowers these designers to create their best performing designs.

One example of this is in engine thermal simulation, where the temperature field on the cylinder head and block, shown below in Fig. 31. Exploring this temperature result in virtual reality provides more insights and understanding than viewing static images. Here one can see high temperatures where the exhaust gas leaves the cylinder head.

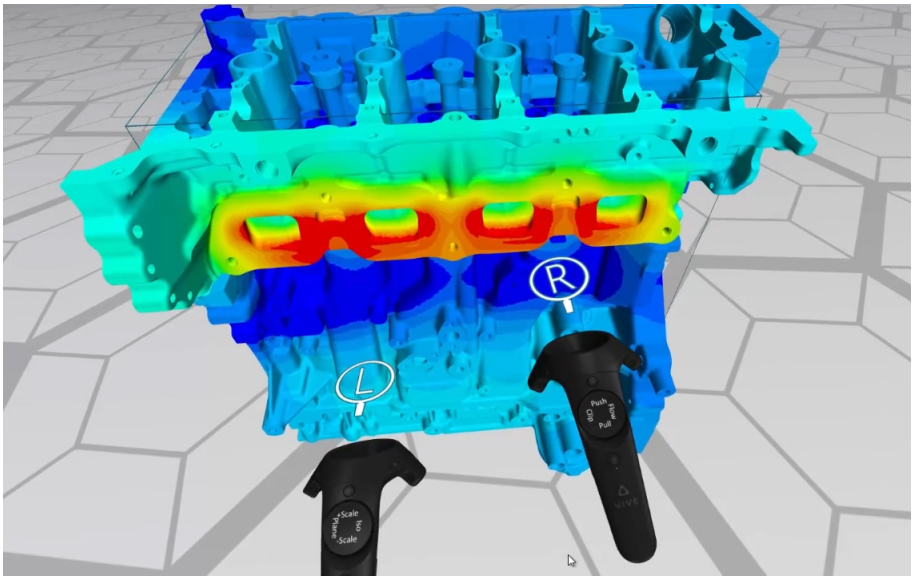


***Fig. 31** Engine Temperature Contour in Virtual Reality, courtesy of General Motors.*

Further intuition comes from cutting through the surfaces and visualising the flow field inside the cooling jacket, as shown below in Fig. 32. This demonstrates the impact of geometry to flow and the impact of flow

to temperature. Where low velocity is observed (blue particles), the cooling wall temperature is higher (yellow vs green of neighbouring cylinders). This is an example where the image illustrates the relationship, but experiencing this result within the immersive VR environment creates a significantly stronger connection in the mind of the viewer – a connection that must be experienced to be fully appreciated.

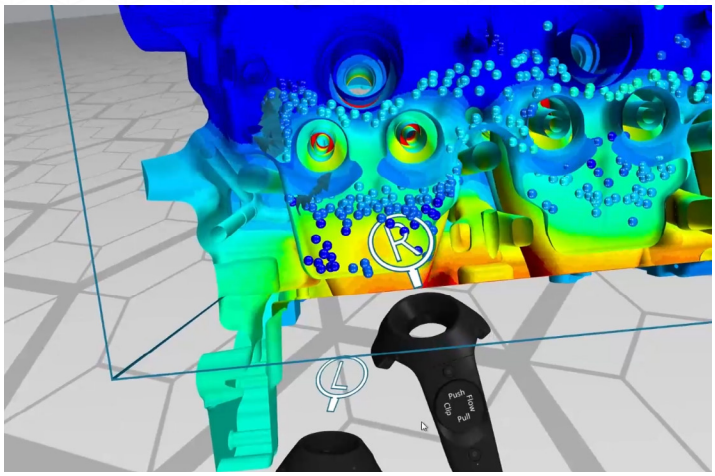


***Fig. 32** Inserting flow particles into geometry cutaway, courtesy of General Motors.*

Viewing the flow distribution in a turbocharger cooling jacket, seen below in Fig. 33, allows the designer to target specific flow distributions – ensuring high cooling performance and eliminating flow dead zones which can lead to temperature spikes or cause localised boiling. This specific visualisation includes both particle tracers (spheres) as well as coloured volume (green/yellow near inlets and outlets).

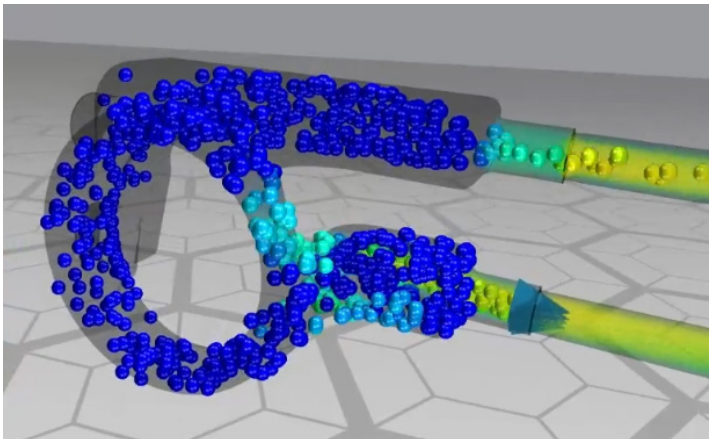


***Fig. 33** Turbocharger cooling jacket flow distribution, courtesy of General Motors.*

4.2 Key drivers and benefits

As introduced earlier in this document, the automotive industry is undergoing a profound transformation driven by digital technologies. Among these, immersive simulation stands out as one of the gamechangers. It enables manufacturers to visualise, test, and refine designs in highly realistic virtual environments, reducing reliance on physical prototypes and accelerating innovation. This approach not only improves efficiency but also enhances collaboration and customer-centricity. Below, we explore four critical areas where immersive simulation delivers measurable benefits: Lead Time Reduction, Collaborative Design, Cost to Design, and Customer Experience Evaluation.

4.2.1 Lead time reduction

Reducing lead time is one of the most significant advantages of immersive simulation in automotive development. Traditionally, creating physical prototypes and conducting validation tests can take weeks or even months, slowing down the entire product lifecycle. Immersive technologies allow engineers to build and test virtual prototypes almost instantly, enabling rapid iterations and early detection of design flaws. This means potential issues – such as ergonomic constraints, assembly conflicts, or aerodynamic inefficiencies – can be addressed before costly physical models are produced. By integrating XR into the design workflow, companies can compress development timelines dramatically, ensuring faster decision-making and quicker transitions from concept to production. In a market where speed to market is a competitive differentiator, immersive simulation becomes a strategic tool for maintaining agility and responsiveness.

4.2.2 Collaborative design

Automotive design involves multiple stakeholders, often spread across different countries and time zones. Immersive simulation creates a shared virtual environment where designers, engineers, suppliers, and even marketing teams can interact with full-scale 3D models in real time. This eliminates the need for physical meetings and reduces communication gaps that often lead to misunderstandings or delays. Teams can review complex assemblies, assess ergonomics, and validate design intent collaboratively, ensuring alignment across departments. Moreover, immersive platforms allow for simultaneous feedback and decision-making, which accelerates consensus and reduces the risk of costly late-stage changes. By fostering transparency and inclusivity, these tools enhance creativity and innovation, making collaborative design not only more efficient but also more dynamic and engaging.

4.2.3 Cost to design

The financial impact of immersive simulation is substantial. Traditional prototyping requires expensive tooling, material consumption, and multiple iterations, all of which contribute to high development costs. Immersive technologies replace these physical prototypes with virtual models that can be modified quickly and at minimal expense. This approach reduces material waste and eliminates the need for repeated manufacturing of test components. Additionally, early identification of design flaws prevents costly rework during later stages of development. Beyond design, immersive simulation also supports virtual training and maintenance planning, reducing operational costs and improving workforce readiness without physical resources. Overall, the cost savings achieved through immersive simulation free up budgets for innovation and allow companies to allocate resources more strategically.

4.2.4 Customer experience evaluation

Customer expectations for comfort, aesthetics, and usability are higher than ever, and immersive simulation provides a powerful way to meet these demands. Virtual showrooms and interactive experiences enable OEMs to test interior layouts, visibility, and user interface ergonomics with real customers or focus groups before production begins. This early feedback loop ensures that vehicles align with consumer preferences, reducing the risk of post-launch dissatisfaction. Immersive tools also allow designers to simulate real-world driving scenarios, helping evaluate factors such as dashboard readability, seat comfort, and accessibility. By integrating customer insights into the design process, manufacturers can deliver products that resonate with market trends and strengthen brand loyalty. Ultimately, immersive simulation transforms customer experience evaluation from a late-stage activity into a proactive, data-driven process that enhances product appeal and competitiveness.

4.3 Pending challenges

The following is a non-exhaustive list, in no particular order of priority, of challenges to address for a large-scale deployment of XR in the automotive industry. It should be noted that these challenges are often interdependent.

4.3.1 Hardware ergonomics and comfort

XR devices must balance performance with wearability. Heavy headsets cause fatigue, while poor weight distribution leads to discomfort during extended sessions. Compliance with safety standards adds complexity. Miniaturisation of sensors and batteries without overheating is still a major hurdle. Comfort is critical for adoption in both consumer and industrial contexts.

4.3.2 Visual quality and field of view

Achieving high-resolution displays with wide FoV is essential for immersion. Accurate colour management through spectral rendering and high-fidelity display is critical to replicate natural human perception under varying observation conditions. This requires advanced photometric calculations and dynamic adaptation to mixed reality lighting environments. In this respect, considering lighting conditions in mixed reality is crucial.

4.3.3 Interaction and usability

Users expect natural interaction – voice, gesture, and haptic feedback – but reliability varies across environments. Gloves, noise, and protective gear complicate gesture and voice recognition in industrial settings. Interfaces must avoid cognitive overload while supporting complex workflows. Seamless multimodal input is still far from perfect.

4.3.4 Connectivity and integration

XR requires low-latency, high-bandwidth connections for real-time rendering and data sync. Factories with metal structures create interference, making stable Wi-Fi or LTE difficult. Professional XR must integrate with ERP, MES, and PLM systems for operational efficiency. Still XR struggles with cloud streaming for high-quality experiences. Reliable connectivity is a prerequisite for scaling XR solutions.

4.3.5 Data security and ecosystem

XR devices capture sensitive data – confidential models, video, and audio for example – raising IP and privacy concerns. Compliance with GDPR and industrial security policies is mandatory for professional use. Lack of standardised platforms slows content development and interoperability. Building a secure, scalable ecosystem is key for widespread adoption.

Chapter 5: XR market outlook

5.1 Global overview 2026–2035: where is XR heading?

5.1.1 Market size and trajectory

Industry studies consistently point to strong growth in the XR market, but the numbers vary widely depending on what is included: hardware, software, and services. Forecasts for 2030 range from approximately $85 billion to over $1 trillion, reflecting differences in methodology and scope. For instance, Grand View Research projects a market size of $1,069 billion by 2030, driven by a compound annual growth rate (CAGR) of around 33%. In contrast, MarketsandMarkets estimates a more conservative $85 billion by 2029, with a CAGR of roughly 28%. These discrepancies highlight the complexity of defining XR boundaries and the influence of adjacent technologies like AI and edge computing.

IDC adds further perspective, anticipating shipments of 43 million XR devices by 2029, alongside software and services spending of $12 billion in 2025, growing at about 20% annually. While hardware revenues will continue to expand, they are expected to remain volatile due to rapid innovation cycles and pricing pressures. Over the long term, the real value will shift toward software platforms, AI-driven experiences, and managed services delivered via edge and cloud infrastructure. This transition reflects a broader trend in the tech industry: monetisation increasingly comes from ecosystems and recurring services rather than standalone devices.

5.1.2 Device and supply dynamics (2026–2031)

Meta continues to dominate the VR/MR segment with its Quest line and is aggressively expanding into smart glasses through its partnership with EssilorLuxottica (Ray-Ban's parent company), a category experiencing rapid growth thanks to improved form factors and integrated AI assistants. These glasses are positioned as lifestyle devices, blending fashion with functionality such as hands-free video capture and real-time translation.

Apple Vision Pro, launched as a premium mixed reality headset, has seen adoption primarily in enterprise context – design reviews, immersive training, and collaborative workflows – while consumer uptake remains below initial expectations due to high pricing and limited everyday use cases. Apple is reportedly working on lighter, more affordable versions and exploring AR glasses as part of its long-term roadmap, aiming for mass-market appeal.

Other players are shaping the landscape: Sony continues to focus on PlayStation VR for gaming, while Varjo targets high-end enterprise and simulation markets. XREAL (formerly Nreal) is gaining traction with AR glasses optimised for portability and entertainment. Lenovo and HTC maintain presence in enterprise VR, and Qualcomm powers many XR devices with Snapdragon XR platforms. Meanwhile, Samsung and Google are entering the XR space with advanced AR wearables.

A notable trend reversal is underway: the VR consumer market has been declining due to the absence of "killer apps" and fatigue around bulky headsets. However, analysts expect a rebound between 2026 and 2029, driven by mixed reality and lightweight AR glasses integrated with AI for contextual assistance, productivity, and immersive social experiences. This shift signals a move from isolated VR experiences toward seamless, everyday augmented interactions.

5.1.3 Standards and interoperability

OpenXR 1.1 (Khronos, 2024) consolidates critical extensions and establishes a unified foundation for XR platforms such as Meta, Microsoft, Sony, Varjo, XREAL, and Qualcomm, as well as leading engines like Unity, Unreal, Omniverse, and Blender. This standardisation significantly reduces fragmentation, simplifies integration, and accelerates cross-platform development. By harmonising APIs and runtime behaviour, OpenXR enables developers to deliver consistent XR experiences across diverse hardware and software ecosystems, lowering costs and improving scalability. It also fosters innovation by freeing resources previously spent on compatibility work, allowing teams to focus on advanced features like spatial computing and immersive collaboration.

Complementing this, the OpenUSD standard is becoming the backbone for interoperable 3D content workflows. OpenUSD provides a robust, extensible framework for describing complex scenes, assets, and behaviours, enabling seamless collaboration between tools and platforms. Its ability to handle high-fidelity, scalable data exchange is critical for digital twins, virtual production, and industrial XR applications. When combined with OpenXR's runtime interoperability, OpenUSD ensures that rich 3D environments can be synchronised and rendered consistently across devices and engines. Together, these standards form a powerful foundation for next-generation XR ecosystems, driving efficiency, creativity, and real-time collaboration.

5.1.4 Networks and latency: 5G-advanced to 6G (2030+)

The 3GPP roadmap is paving the way for 6G/IMT-2030, introducing native AI capabilities, ultra-low latency, and highly accurate positioning. These innovations will unlock next-generation immersive experiences, such as real-time XR collaboration and large-scale digital twins. 6G aims to overcome current limitations by delivering reliable connectivity for critical and interactive applications. Embedded AI will optimise network and service management, ensuring adaptive and intelligent performance. To support these demanding use cases, edge computing infrastructure will be essential, bringing processing power closer to users and minimising delays. This convergence of advanced networks, AI, and edge will be the foundation for seamless and highly immersive XR environments.

In parallel, Wi-Fi technology has evolved dramatically to complement cellular advancements. From early standards to Wi-Fi 6 and 6E, improvements in throughput, latency, and multi-user support have enabled robust wireless experiences. The arrival of Wi-Fi 7 introduces multi-gigabit speeds, ultra-low latency, and multi-link operation across 5 GHz and 6 GHz bands, making it ideal for high-definition XR streaming and collaborative design reviews. These capabilities allow automotive and industrial environments to deploy wireless immersive solutions without compromising performance. Together, 6G and next-generation Wi-Fi will create a hybrid connectivity ecosystem, ensuring seamless, high-bandwidth experiences for real-time simulation, digital twins, and interactive collaboration.

5.2 XR scenarios (2030–2035)

Between 2030 and 2035, Extended Reality (XR) technologies are expected to evolve dramatically, reshaping how we work, learn, and interact with digital content. Driven by advances in connectivity, AI, and hardware miniaturisation, XR could range from a ubiquitous, everyday interface to a specialised tool for industrial applications – or even face stagnation under regulatory and economic pressures. To anticipate these possibilities, we outline four distinct scenarios that explore the spectrum of outcomes: from "Spatial Everywhere," where XR becomes as common as smartphones, to "Utility XR," focused on enterprise productivity; from "Fragmentation & Slowdown," where adoption stalls, to a "Disruptive Leap" powered by neural interfaces and holographic displays. These scenarios provide a strategic lens for understanding potential trajectories, guiding investment, innovation, and policy decisions in the coming decade.

5.2.1 Optimistic scenario – "Spatial everywhere"

In this vision, XR becomes truly ubiquitous across work, industry, and daily life, evolving into a seamless layer of digital interaction. Lightweight AR glasses under 70 grams feature sleek designs, adaptive lenses, and comfortable ergonomics for all-day wear. Battery life exceeds six hours thanks to ultra-efficient processors, advanced thermal management, and edge-assisted connectivity. AI copilots integrated into these devices provide real-time assistance, contextual information, and predictive workflows, transforming how we interact with data and environments. Standards like OpenXR and OpenUSD achieve widespread adoption, ensuring interoperability across platforms, engines, and content pipelines. This convergence accelerates enterprise and consumer use cases – from immersive collaboration and digital twins to AI-driven design, remote support, and even personalised learning. Spatial computing becomes as common as smartphones today, with XR interfaces replacing traditional screens in offices, vehicles, and homes. Retail, healthcare, and education embrace XR for hyper-personalised experiences, while entertainment evolves into persistent mixed-reality worlds. In this scenario, XR is not just a tool, it becomes the default interface for the digital age.

5.2.2 Central scenario – "Utility XR"

Here, XR establishes itself as a critical enterprise tool but remains a niche for consumers. Adoption is strong in sectors like manufacturing, healthcare, logistics, and training, where XR delivers measurable ROI through improved productivity, reduced errors, and enhanced safety. Digital twins, immersive simulations, and remote collaboration dominate the value proposition, enabling predictive maintenance and real-time operational insights. Hardware innovation continues, but the real growth shifts toward software ecosystems, AI-enhanced workflows, and managed services delivered via edge and cloud platforms. Companies invest in XR as part of Industry 5.0 strategies, integrating it with IoT and robotics for smart factories. Consumer uptake is slower due to cost, form factor, and limited everyday applications, keeping XR primarily a professional utility rather than a mainstream lifestyle technology. Gaming and entertainment remain niche XR drivers, but mass adoption stalls until breakthroughs in affordability and comfort occur. In this scenario, XR is essential for business transformation but optional for personal life.

5.2.3 Pessimistic scenario – "Fragmentation and slowdown"

In this outcome, XR faces significant headwinds that stall its evolution. Supply chain disruptions limit hardware availability and drive-up costs, while stringent regulations around privacy, safety, and biometric data slow deployment. The absence of compelling daily-use applications and lack of interoperability between platforms lead to fragmentation, frustrating developers and enterprises alike. Competing standards and proprietary ecosystems create silos, reducing scalability and innovation. Consumer interest stagnates as devices remain bulky, expensive, and energy-hungry, confining XR to specialised B2B sectors such as aerospace, defence, and high-end industrial design. Investment shifts toward other emerging technologies like quantum computing or AI-driven automation, leaving XR as a niche solution rather than a transformative platform. In this scenario, XR survives but fails to thrive, becoming a tool for specific technical workflows rather than a universal interface for digital interaction.

5.2.4 Disruptive scenario – "Neural and holographic convergence"

In this trajectory, XR takes a quantum leap by fusing non-invasive neural interfaces with holographic/light-field display systems, making interaction nearly frictionless and screens largely optional. Lightweight headsets (and select form-factor bands or earbuds) capture subtle neural and bioelectric signals (e.g. EEG, EMG, eye-tracking, and micro-gestures), enabling intent-driven control that feels natural and hands-free.

On the visual side, true-to-life holography and advanced light-field optics render volumetric content with correct accommodation/vergence, while spatial audio creates richly layered soundfields, allowing digital objects to coexist convincingly with the real world. Edge-accelerated multimodal AI copilots parse gaze, intent, environment semantics, and task context to orchestrate complex workflows – think designing, simulating, and validating a digital twin with a few spoken hints and a glance. Networking stacks blend deterministic 6G and Wi-Fi 7/8 for ultra-low latency and high reliability, while neuromorphic accelerators on-device cut power draw and preserve privacy by processing sensitive signals locally. Content pipelines evolve beyond standard engines: OpenXR/OpenUSD combine with scene graphs, graph-based ML, and streaming ray-tracing to deliver photorealistic, interactive holograms in dynamic industrial spaces. New UX primitives emerge – thought-initiated shortcuts, contextual holographic dashboards, collaborative volumetric canvases – reshaping productivity in design, healthcare, logistics, and education. With this power come challenges: neuro-ethics, consent frameworks for brain-adjacent data, safety certifications for optical energy and long-duration wear, and robust fail-safes against intent misclassification. If these hurdles are addressed, XR becomes a screenless, ambient computing layer and a pervasive, holographic interface that augments human capability without encumbering it.

Chapter 6: Conclusion

As the automotive industry undergoes one of the deepest transformations in its history, immersive simulation emerges as a foundational capability rather than an optional innovation. Electrification, software-defined vehicles, advanced driver assistance systems, and ever-shorter development cycles all demand tools that can integrate complexity while keeping humans at the centre of the design process. XR simulation – powered by high-fidelity visualisation, interactive environments, and accurate perception modelling – provides this essential bridge between digital intent and real-world experience.

To unlock its full potential, however, no single company can succeed alone. A robust ecosystem is required, bringing together OEMs, suppliers, research institutions, hardware manufacturers, and software editors. Their collective contributions – ranging from spatial computing engines to material-accurate rendering pipelines – form the technological backbone that enables immersive simulation at scale. This ecosystem must rely on open, industry-wide standards, such as OpenXR and OpenUSD, to ensure interoperability, preserve digital investments, and support collaboration across heterogeneous toolchains. Standards reduce friction, accelerate adoption, and allow simulation data to become a strategic asset shared across programs, partners, and regions.

Software editors will continue to play a decisive role by delivering more specialised, domain-aware tools, capable of handling complex 3D data, real-time physics, advanced haptics, and multi-user XR environments. Their ability to integrate seamlessly with PLM, CAD, manufacturing systems, and data-driven workflows will define the maturity of immersive simulation in the coming decade.

Finally, the impact of artificial intelligence will be transformative. AI accelerates the creation of virtual worlds, automates material and lighting calibration, synthesises rare driving scenarios, and augments human perception through intelligent assistance. Combined with XR, AI will turn simulation into a self-improving system, capable of learning from usage data, adapting to new contexts, and scaling across the vehicle lifecycle – from early concept to homologation and field operations.

The path forward is clear: immersive simulation, strengthened by open standards, a vibrant ecosystem, and AI-powered innovation, will become a strategic cornerstone for automotive development. Companies that invest now in these foundations will gain decisive advantages in quality, speed, collaboration, and customer-centricity, shaping not only the vehicles of tomorrow, but the way we design and experience mobility itself.

Glossary

Abbreviation	Meaning
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AR	Augmented Reality
AV	Augmented Virtuality
BRDF	Bidirectional Reflectance Distribution Function Bidirectional
BSDF	Scattering Distribution Function
CAE	Computer Aided Engineering
CAGR	Compound Annual Growth Rate
CAD	Computer-Aided Design
CAVE	Cave Automatic Virtual Environment
CD/m^2	Candela per square metre
CFD	Computational Fluid Dynamics
CGI	Computer-Generated Imagery
CMF	Colour, Material and Finish
CPU	Central Processing Unit
CUDA	Compute Unified Device Architecture
DIL	Driver in the Loop
EEG	Electroencephalography
EMG	Electromyography
ERP	Enterprise Resource Planning
FPS	Frames Per Second
FOV	Field of View
GLTF	GL Transmission Format
GPGPU	General-Purpose computing on Graphics Processing Units
GPU	Graphics Processing Unit
GRF	General Reflectance Function
HDR	High Dynamic Range
HPC	High-Performance Computing
IDC	International Data Corporation
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISO	International Organisation for Standardisation
JT	Jupiter Tessellation file format
LCD	Liquid Crystal Display

Glossary

Abbreviation	Meaning
LOD	Level of Detail
LTE	Long-Term Evolution
MES	Manufacturing Execution System
MR	Mixed Reality
OpenGL	Open Graphics Library
OpenUSD	Open Universal Scene Description
OpenXR	Open Extended Reality (standard)
OST	Optical See-Through
PBR	Physically Based Rendering
PLM	Product Lifecycle Management
PLMXML	Siemens-developed PLM XML software
STL	Stereolithography file format
UI	User Interface
USD	Universal Scene Description
UV	Ultraviolet (in graphics usage: UV texture coordinates)
VE	Virtual Environment
VR	Virtual Reality
VST	Video See-Through
XR	Extended Reality