Turning Automotive Windows into the Ultimate HMIs

New technologies promise to transform vehicles' windows into bright, vivid, full-motion video-capable displays. Here, we take a closer look at the potential applications and trends in window displays and how they'll change the driving experience.

by **Michael Firth**

CONNECTED VEHICLES EQUIPPED WITH ONBOARD processing power and advanced sensors that collect gigabytes of data are becoming the norm in the automotive industry. As a result, the often-overlooked world of human-machine interface (HMI) design is now in the limelight. Indeed, automotive original equipment manufacturers (OEMs) increasingly focus their resources on creating effective, intuitive HMIs to better leverage technological advancements in today's vehicles.

One area of particular interest is the use of windows as an HMI display, which enables communication with drivers, passengers, and the outside world. Thus, here I explore potential applications and technologies for automotive window displays.

Augmented Reality Head-Up Displays

Head-up displays (HUDs) are a great example of how to use a vehicle's windscreen as a display. General Motors (GM) was the first to embrace the technology: In 1988, it built 50 Indy Pace Car edition Oldsmobile convertibles equipped with HUDs that projected a digital speedometer and turn-signal indicators. Much like today, GM's original HUD displayed basic information via a relatively small two-dimensional (2D) image that floated out near the car's front bumper. With technological advancements in today's vehicles—such as advanced driver assistance systems (ADAS) and onboard navigational systems, there is a need for a more effective HMI. To support this requirement, OEMs are working on next-generation augmented reality (AR) HUDs, as **Fig. 1** shows.

Unlike traditional HUDs, AR HUDs have a wider field of view (FOV) and can interact with more of the real-world road scene. They also project graphics further out, enabling graphics to fuse with and mark real-world objects. To create the illusion of fusion with the real world, the graphics must be projected out a minimum of 7 meters (m) from the driver. The overall visual effect and driver experience improve when graphics are projected out even further, with the majority of AR HUDs supporting 10- to 15-m projection distances. The distance at which the graphics are projected is called the virtual image distance (VID).

Among the key challenges in designing an AR HUD are meeting luminance, solar irradiance, and size requirements. If you double the display's area, you must increase the HUD imaging source's light output by an equal factor. The same relationship holds true for the eye box: Doubling the eye-box area doubles the required light. Double the eye box and display area, and you'll need to increase the light output by a factor of four. Choosing an efficient imaging

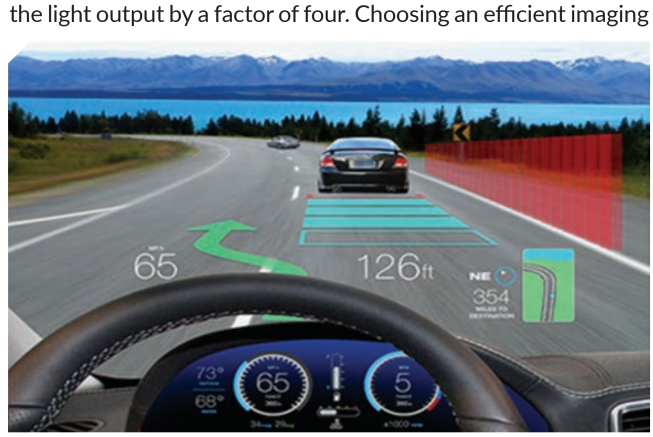


Fig. 1.

Example of an augmented reality head-up display (AR HUD).

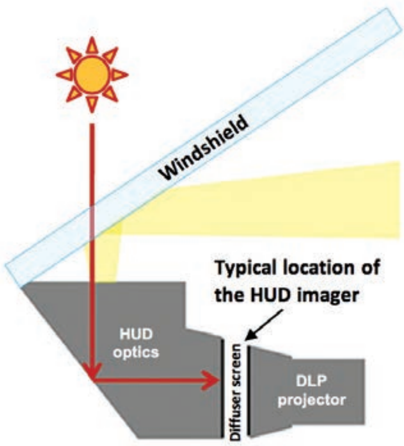


Fig. 2.

How solar irradiance concentrates on the HUD imager.

technology that can meet luminance, power, and thermal requirements is an important step in the AR HUD design process.

Managing solar irradiance **(Fig. 2)** in today's traditional HUDs already poses a significant design challenge. Managing solar irradiance in an AR HUD (with a VID of 10 m or more and a large FOV that lets in more of the sun's energy) is even more difficult. The higher optical magnification of an AR HUD concentrates the solar irradiance to levels that easily can damage the HUD's imager panel. Solar irradiance must be determined carefully, with the AR HUD designed to handle a worst-case temperature rise without derating or turning off.

With its use of an intermediate diffuser screen as the image source for the HUD, DLP technology has excellent solar irradiance performance. The diffuser screen passes and disperses the concentrated solar irradiance, limiting the temperature rise (on the diffuser's surface and the AR HUD's interior) to manageable levels.

By far, the most significant challenge in AR HUD design today is size. With a traditional optics approach that uses a fold mirror and a large aspherical mirror **(Fig. 3)**, the HUD's size easily can approach 20 liters (20,000 cm^3). Most OEMs simply don't have this much free space in the dash. To solve this problem, the industry is exploring waveguide and holographic film technologies.

In a waveguide, light is injected into a small port at one end and travels along the waveguide via multiple total internal reflections. Holographic or diffractive optical elements are then used to emit portions of the light along the length of the waveguide. This expands the beam and preserves the incoming light's ray angle, also known as pupil expansion (**Fig 4**).

Fig. 3.

A traditional mirror-based optics HUD.

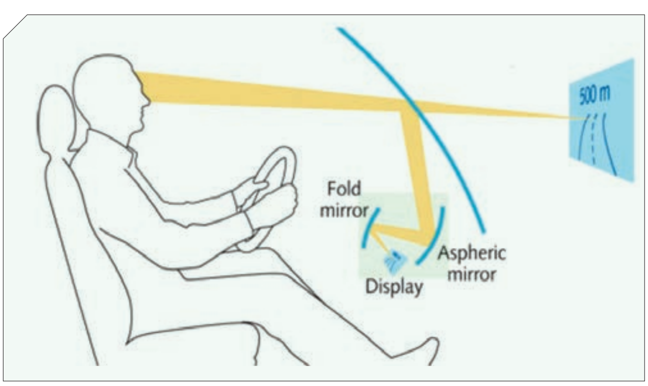
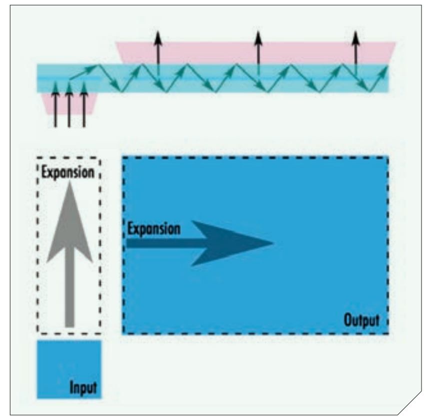


Fig 4.

Illustration of a simple waveguide expansion.



A holographic film has microscopic structures that have been printed into the film and designed to act as a holographic optical element (HOE). The HOE can be designed to replace traditional optical elements such as lenses and mirrors. In a HUD, the HOE typically is designed to replace the large aspherical mirror. Both waveguides and holographic films significantly shrink package volumes, making it easier to fit an AR HUD into the vehicle's dash. Both technologies use advanced optical elements to replace traditional mirrors. Waveguides are installed in the vehicle's dash similar to traditional HUDs, but their height and overall package volume are significantly smaller. With a holographic AR HUD, a small projector with magnification optics is installed in the dash and a holographic film

Fig. 5.

Top: A waveguide-based AR HUD.
Bottom: A holographic film-based AR HUD.

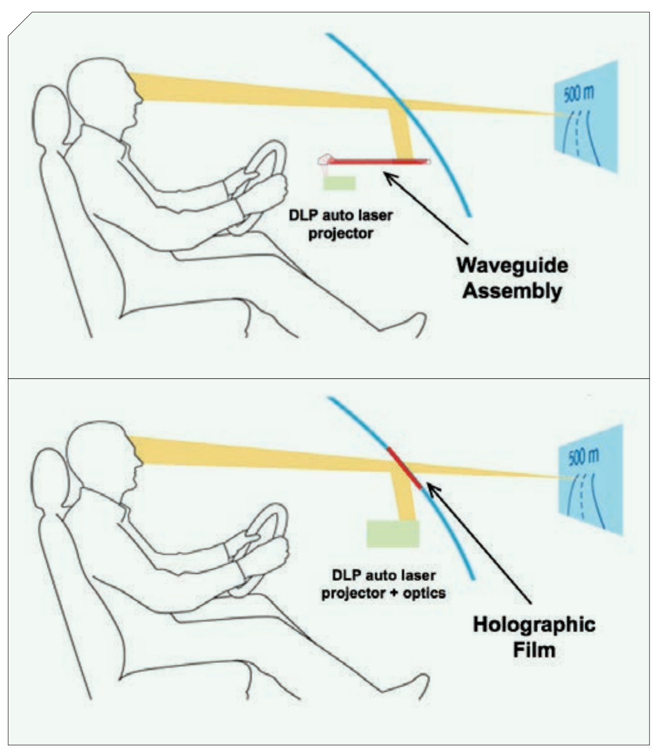


Fig. 6.

Windscreen cluster image.

is laminated into the windscreen. **Fig. 5** shows AR HUDs based on a waveguide and holographic film, respectively. These new technologies not only shrink HUD package size but also enable much larger FOVs, supporting HUDs with 15 x 5-degree FOVs or larger. Both waveguides and holographic AR HUDs require laser-based light sources.

DLP technology is light source-agnostic and supports both laser and LED illumination sources, making it an excellent imager choice for these new technologies. OEMs are working to bring both waveguide and holographic film AR HUDs to market by 2025.

Instrument Cluster Windscreen Displays

Instrument clusters are look-down displays that require drivers to take their eyes off the road, resulting in distracted driving and longer reaction times. HUDs set out to solve this problem by placing critical driving information in the driver's line of sight, improving situational awareness and reaction times. But, as we now know, HUDs can require substantial dash space. Instrument clusters can easily approach 15 inches or more in width, which would require a very large HUD to reproduce. One option to minimize dash space is an in-plane (IP) holographic windscreen display; **Fig. 6** illustrates an example.

An IP holographic windscreen display is a type of HUD that projects graphics directly onto the windscreen. As with a traditional HUD, the display is viewable via the eye box; but unlike a traditional HUD, there is no VID. (That is, the graphics are not projected out in front of the car.) An IP holographic windscreen display gives up a long VID in return for a much smaller package size.

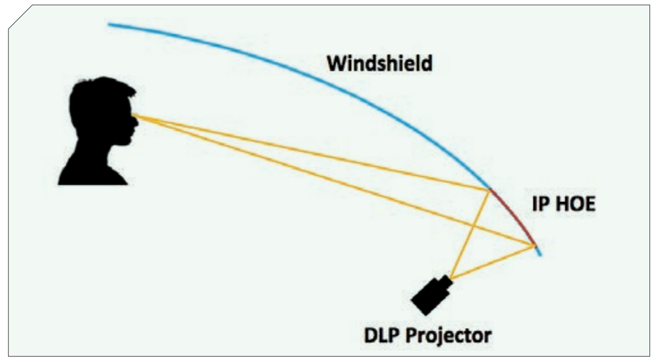


Fig. 7.

Example projector placement.

The advantage of a long VID is less eye fatigue and quicker reaction times. The further the graphics are projected out in front of the driver, the easier it is for the driver to change focus from the road scene to the projected graphics, resulting in less eye fatigue, quicker focus times, and faster response times. This change in eye focus from one object to another at different distances is known as accommodation.

Giving up a long VID for a smaller package size is a reasonable tradeoff given the advantages of a windscreen cluster. A windscreen cluster eliminates drivers' need to look down and can project a large, bright display in a broad range of vehicles, with significantly reduced package sizes and a relatively quick time-to-series production. **Table 1** shows a comparison of a traditional look-down cluster to several different HUD technologies.

In an IP holographic windscreen cluster, a small projector mounted into a vehicle's dash illuminates an HOE film laminated into the front windscreen. **Fig. 7** shows an example of how to place the projector. The projector is less than a liter in size, fitting easily into the vehicle's dash. The target display size is on the order of a 15 x 5-degree to 25 x 10-degree FOV, which is large enough to project a full-sized instrument cluster onto the windscreen.

Like an AR HOE, an IP HOE has some interesting optical properties that are advantageous for HUDs. One advantage is that it is possible to design an HOE such that the angle of incidence for light from the projector needn't equal the angle of reflection **(Fig. 8)**. This enables flexibility in projector placement and the ability to support a large range of windscreen angles (rake angles). From a geometric perspective, not needing equal angles greatly

TECHNOLOGY	PACKAGE SIZE	IMAGE DISTANCE	ACCOMMODATION TIME (eye fatigue, missed objects)	LOOK-DOWN ANGLE (time with eyes off the road)
Traditional cluster	++	+ (shortest)	+++++ (longest)	+++++ (longest)
IP HOE HUD	+ (smallest)	++	+++	++
Traditional HUD	+++	+++	++	++
AR HUD	+++++ (largest)	+++++ (longest)	+ (shortest)	+ (shortest)

Table 1.

Comparison of HUD technologies versus a traditional cluster. Green text = best; Red text = worst.

Fig. 6-8: Courtesy of Ceres Holographics. All other figures courtesy of the author.

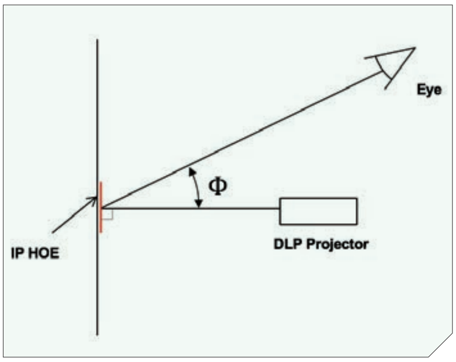


Fig. 8.

In an HOE, the angle of incidence doesn't have to equal the angle of reflection.

simplifies the design, especially for small sports cars (with quite low windscreen angles) and semi-trailer trucks (with almost 90-degree windscreen angles).

The mass production of HOEs requires creating a master HOE that's copied using a high-volume manufacturing printing process. The master can be recorded through an analog or digital recording process. The challenge with an analog recording process is that the entire hologram is recorded at once over several minutes of exposure time, and any vibration or thermal expansion of the film during the recording process can cause degradation and artifacts in the hologram. The digital recording method records the hologram on a pixel-by-pixel basis, minimizing sensitivity to vibration and thermal expansion with much shorter individual pixel exposure times (for example, < 1 millisecond). Other advantages include improved accuracy, repeatability, and ease of precompensation for windscreen curvature. The latter enables car manufacturers to compensate for windscreen distortion effects and to support different windscreens in software versus hardware, thereby simplifying the design process.

Other advantages of an HOE include an extremely bright display (> 12,000 candelas per square meter [cd/m^2]), eliminating the windscreen wedge (no double image), and seeing images even when wearing polarized sunglasses.

Table 2.

Comparing an IP HOE and AR HOE.

FEATURE	IP HOE	AR HOE
Package size	< 1 liter	3 to 10 liters
Long VID	No: real image projected at the windscreen	Yes
Viewable with polarized sunglasses	Yes	Yes
Windscreen wedge	Not required	Not required
HOE lamination difficulty	+ (easier)	+++ (difficult)
Sunlight visual artifacts	Minimal	Some
Illumination source	LED	Laser

From a vehicle series production perspective, IP HOEs are less challenging than AR HOEs. Compared to AR HOEs, IP HOEs are easier to laminate into the windscreen, have significantly fewer parasitic optical artifacts caused by sunlight, and are more forgiving of windscreen tolerances. Ceres Holographics, one of the pioneers in digital automotive holography, estimates that windscreen clusters could be in production as early as 2023. **Table 2** compares the features of an IP HOE to an AR HOE.

Transparent Window Displays

With the recent focus on autonomous driving and ride-hailing services, a type of display known as the transparent window display (TWD) has become increasingly attractive to mobility service providers. A TWD uses the vehicle's windows to support two distinct states: a transparent state and a display state. When in the transparent state, the TWD looks identical to the other windows in the vehicle. When in the display state, however, it

Fig. 9.

Top: Short throw DLP projector mounting option. Short throw projector optics allow the projector to be placed closer to the side window. Bottom: Standard throw DLP projector mounting option.

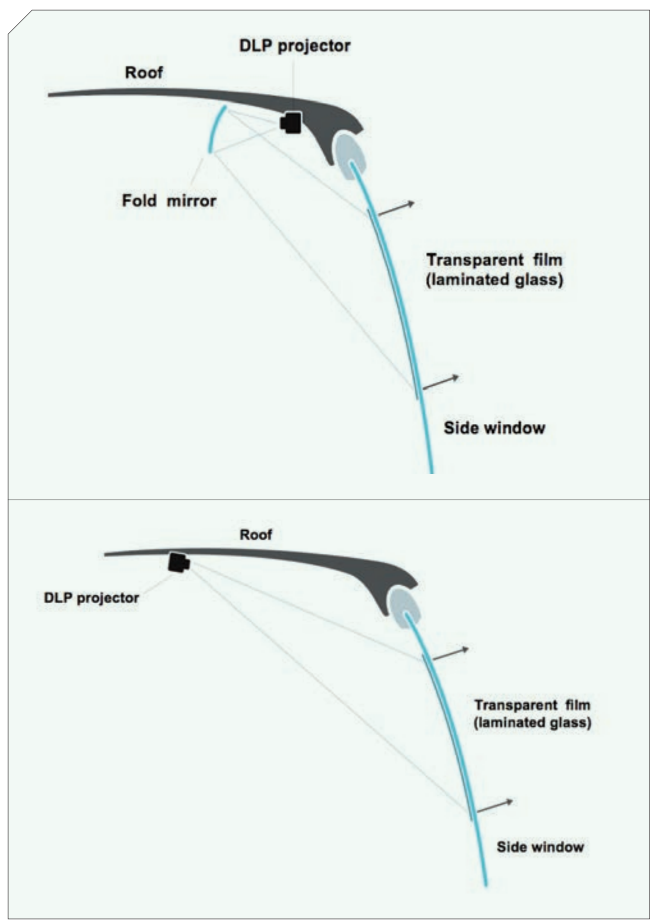


Fig. 10.

Transparent window display (TWD) application examples. L4/5 stands for level 4 (high driving automation) or level 5 (full driving automation).

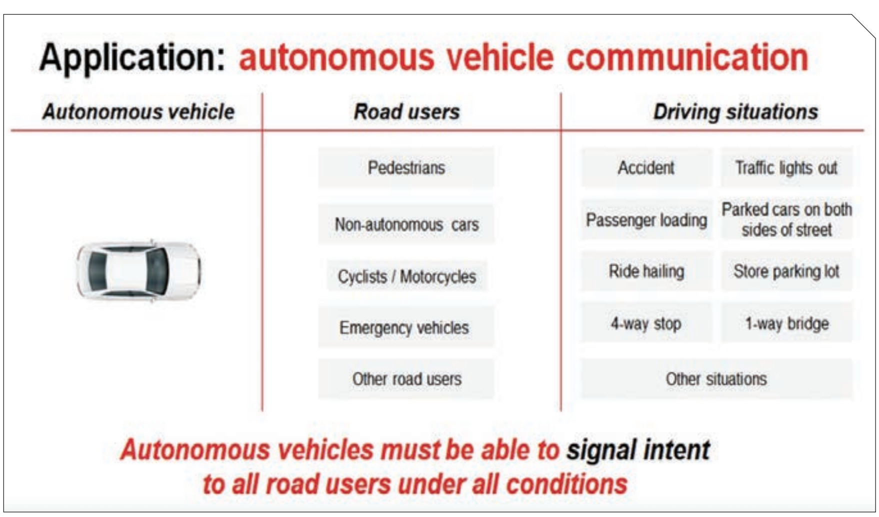
presents full-color text, graphics, or video. A TWD combined with touchscreen technology enables an easy-to-use HMI for the driver or passengers.A projector-based TWD consists of a small projector mounted to the interior roof surface or other location in the vehicle **(Fig. 9)** and a transparent film laminated into the vehicle's side, rear, or front window. The projector projects text, graphics, or full-motion video onto the transparent film, which, when in the display state, acts as a projector screen.

There are numerous film options (some already automotive-qualified), including 405-nanometer (nm) emissive phosphor, smart glass, nanoparticle, and holographic. Each type of film has different optical properties, including luminance, optimal viewing angle, screen gain, haze, transparency, efficiency, and ease of lamination into the windscreen. Target TWD applications include ride-sharing and ride-hailing, vehicle-to-vehicle and vehicle-to-pedestrian communication, in-car entertainment, driver greetings, vehicle diagnostics, and advertising. Depending on the application, one film may be a better choice than others. (**Fig. 10** shows application examples.)

Companies such as Uber, Lyft, Car2Go, and DiDi can now equip their vehicles with TWDs that enable easy vehicle identification. A side- or front-window TWD can display the rider's name, destination, and unique identification code (which is also sent to the rider's phone) to securely identify the correct car.

Fig. 11.

L4/5 autonomous vehicle communication requirements.



Autonomous vehicles, by definition, don't have drivers, which presents a communication problem. During everyday driving, there are many situations that require one vehicle to signal intent to another vehicle or pedestrian. For example, how does an autonomous vehicle communicate that it "sees" a pedestrian and that it's okay to cross in front of the car? Which car goes first at a four-way stop? **Fig. 11** shows examples of driving situations that require communication. A TWD is an excellent communication option for autonomous vehicles; it does not impact vehicle styling and can be positioned near the top of a vehicle's windows so that it's highly visible.

For ride-hailing and ride-sharing companies, the ability to run ads on the vehicle's windows can generate a monthly revenue stream that increases profits or driver wages. It's possible to run geotargeted advertising campaigns based on the vehicle's location and time of day. For example, during the morning commute, Starbucks ads could run every time a vehicle is within 100 m of a Starbucks location. Autonomous vehicle services also are interested in advertising applications. The autonomous pods showcased in the media and at trade shows, such as the Consumer Electronics Show, have a substantial amount of window area that could be transformed into screens for bright, dynamic advertisements.

Driver greetings and vehicle diagnostics are another intriguing TWD application. The driver-side window can display the percentage of remaining battery charge, tire pressure, and distance to the final destination, as well as greeting drivers as they approach the vehicle. Greetings and information displayed could be customized for different drivers, based on their key fob or cellphone, or even through facial recognition. The driver's window display, when combined with touchscreen capabilities, also could serve as a virtual keypad to lock and unlock the vehicle.

In closing, new technologies are emerging that promise to turn a vehicle's windows into bright, vivid, full-motion video-capable displays. These displays, such as HUDs and TWDs, will be an integral part of advanced HMIs optimized for the needs of drivers, passengers, and the outside world. As with all evolving applications and technologies, challenges will arise. Things may not turn out exactly as predicted, but it's guaranteed to be a fascinating ride.

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