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New film technologies to address limitations in vehicle display ecosystems

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Abstract

Since the introduction of the first modern (i.e., digital) vehicle displays, designers and manufacturers have made significant advances in technologies that improve image quality and enhance unit durability. Typically, these advances have been targeted and discrete. For example, to increase brightness, high efficiency light control films were deployed; to reduce nighttime windshield glare, a light-directing louver film was incorporated into the liquid crystal display (LCD) backlight. While this targeted approach to vehicle display concerns has advanced performance—in many cases impressively—it may have reached the limits of its effectiveness. For displays based on the most common head-up display (HUD) architecture, shortcomings are often interrelated. As such, they require a holistic or cabin human machine interface (HMI) ecosystem approach that recognizes this interplay and, where possible, addresses multiple issues simultaneously. Several new films, in concert with existing film technologies, show how a cabin ecosystem strategy can be implemented.

KEYWORDS

augmented reality (AR), cold mirror technology, efficiency, head-up displays (HUDs), light control film, optical films, reflective polarizer, thermal management, vehicle safety, windshield combiner film

1 | INTRODUCTION

Over the past several decades, advances in consumer electronics have migrated quickly to automotive vehicle displays. In the near future, this migration pattern could be altered: It seems likely that automotive displays will adopt and make commonplace some new technologies before they achieve more than niche application in conventional consumer devices. In particular, head-up displays (HUDs) that incorporate augmented reality (AR)—such as navigation systems that indicate lanes, speed limits, and even road hazards on the windshield—are already available in a range of vehicles, with more on the way.[1,2] Eventually, AR HUD displays will likely be the price of entry for automakers in anything but the lower tier markets.

This move to technology leadership is particularly striking given the uniquely demanding environments in which these automotive displays operate. They must be bright (so they are readable in bright sunlight) but do not produce a windshield glare that would impede nighttime visibility. They must be rugged enough to withstand blasting heat, polar cold, high humidity, and the vibrations from a washboard road, but they must be small and light enough to fit in an increasingly streamlined instrument console.

Several HUD architectures have arisen or are in development in response to these challenges; these include digital micromirror device (DMD) and holographic technologies.[3,4] For the purposes of this paper, we have focused on the most common HUD architecture in use today, which is based on an liquid crystal display (LCD) picture generating unit (PGU) with a two-mirror optical system. When employing this common two-mirror HUD architecture, automotive display manufacturers could address these challenges discretely. Resolution could be improved with the introduction of an upgraded LCD panel; brightness could be improved with more and more powerful LEDs. Today, this approach has reached the limits of its effectiveness. Attempts to improve image quality often create new problems in system durability (usually because of a significant increase in heat) or give rise to unanticipated new image problems (such as ghost images, which we will discuss below).

Future display architectures—and dramatic improvements in existing architectures—could transform how drivers receive information from and about their vehicles. For the near term, advances in the architecture featured below will require a whole-system, cabin human machine interface (HMI) approach that recognizes the interrelationship between image quality, thermal management, system size, and driver safety. Specifically, new applications of multilayer reflective polarizer technology, along with other film technologies, will achieve the desired improvements.

2 | AR HUDS

The development of wider view angle AR HUDs to cover the entire roadway is a good example of how this holistic approach can be efficient and rewarding for display makers.

HUDs have been used in vehicles for decades and offer multiple advantages over displays located below the driver's optimal line of sight; primarily, these displays present critical information to the driver while allowing a constant focus on the road.[5,6] This presentation can be enhanced by incorporating AR functionality into the HUD and expanding the field of view (FOV) to cover the roadway; ideally, the AR would represent a variety of image depths, with some images appearing relatively close to the driver and others in the distance.[7–9]

Notwithstanding these notable benefits, development of AR HUD displays has been slow, due to problems with image quality, system design, and device durability.[10] For example: a primary image quality issue results from conventional windshield construction, in which two glass layers are laminated with an adhesive (typically polyvinyl butryl [PVB]). With current HUD technology, the image reflects off the primary inner glass surface, while an unwanted secondary image or ghost is reflected separately off the outer glass surface. To correct for this artifact, manufacturers can fabricate windshields in which the PVB adhesive layer has a slight wedge shape. The PVB wedge causes the two reflections to become nearly congruent. Unfortunately, this solution works only for drivers within a fairly limited range of heights; taller or shorter drivers will continue to experience some ghosting. Additionally, the performance of wedge adhesives is suboptimal for larger FOVs, as skew light rays (due to the rake and curvature of the windshield) will not be adequately corrected. Furthermore, each new windshield design requires a unique wedge geometry; this complicates design, increases development iteration cycle length, and results in a more complex final manufacturing process.

An additional problem with existing HUD technology derives from the polarity of light generated by current PGUs. These devices generate images using the *S*-polarity of light, which reflects well off of windshield surfaces at most design rake angles. Unfortunately, *S*-pol light is—by design—blocked by polarized sunglasses. As a result, HUD images appear faintly, if at all, to drivers wearing polarized sunglasses.

Finally, HUD development has been hampered by thermal management issues. The temperature within a PGU can ramp up because of both the energy needed to produce a bright, easily readable image in all light environments, and the infiltration of solar energy; the larger aperture required for a full-windshield AR HUD allows even more solar energy infiltration. These high temperatures can affect unit durability and reliability. When HUDs are designed to account for these elevated temperatures, image brightness is sometimes limited. The push to reduce PGU size—concentrating image generation in a smaller and smaller device—compounds these thermal load concerns.

3 | A HOLISTIC APPROACH TO CABIN HMI

Rather than address these issues individually, system designers need to use a whole-system approach that recognizes the interactions between and among components. In particular, the use of multilayer optical polarizing films ensures an efficient and balanced resolution and will ultimately allow for the rapid implementation of some form of AR HUDs.

For almost three decades, multilayer optical films have been key enablers in the development of LCD devices from smaller portable electronics, such as laptops and mobile phones, to huge 120-in TVs. These reflective polarizers and mirror films have been shown to reliably improve display efficiency, typically by 30%–40%.

A suite of such films, along with more conventional infrared (IR) rejection and light control films, promises to bring full-windshield AR HUDs to commercialization.

3.1 | Windshield combiner film

First, a new windshield combiner film (WCF) currently in the final stages of development employs this proven, multilayer optical technology to resolve *S*-pol image visibility and ghosting issues while removing the need for a wedge PVB and simplifying design. It achieves these benefits when paired with a PGU that generates *P*-polarity images (rather than conventional units that generate *S*-pol images).

The WCF is laminated between the panes of windshield glass using a conventional planar PVB adhesive on either side (Figure 1).

WCF is a weak *P*-pol reflector, transmitting a larger portion of incident unpolarized light but reflecting a single *P*-polarity image that is visible under all conditions (day or night, with or without polarized sunglasses) and is insensitive to viewer height (Figure 2).

Crucially, a single image is reflected off the WCF (because *P*-pol light is mostly transmitted through the surfaces on both panes of glass near Brewster's angle of incidence, θ_B).[11] As a result, an adhesive wedge is no longer required to eliminate ghosting. In fact, calculation shows that within about $\pm 5^\circ$ of θ_B the surface-reflected *P*-pol image is less than 1% of image luminance. Not needing a wedge PVB results in significantly improved design flexibility, development speed (a new geometry does not need to be created for each new design), and processability (including higher yields) (Figure 3).

The known inverse relationship between *P*-polarity reflection and visible light transmission (VLT) can be optimized by tuning the WCF to achieve the right balance for each windshield. Tinted glass, for example, will require a different balance between reflection and transmission than a clear glass windshield. In general, the VLT of windshields employing WCF will remain above the mandated 70% transmission. In other words, transmission will be comparable with current windshields, and drivers will not experience any reduced visibility.

Figure 4 shows how the WCF can be tailored (by altering the layer thicknesses, layer configuration, and materials) to achieve a display-maker's preferred balance of reflectivity and VLT for different glass tints and constructions (using a PGU that generates a *P*-pol image). In most instances, an image produced by a WCF-enabled windshield will be of equal or greater

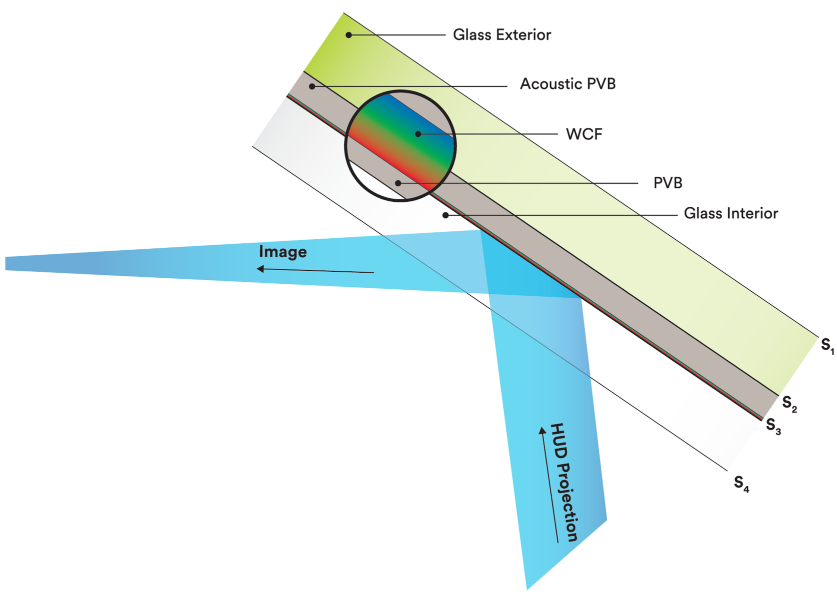

FIGURE 1 Windshield combiner film (WCF) is laminated between planes of a windshield using a conventional polyvinyl butyl (PVB) adhesive. WCF is optimized for an incident angle of approximately 60°, but is relatively insensitive to incident angle. HUD, head-up display

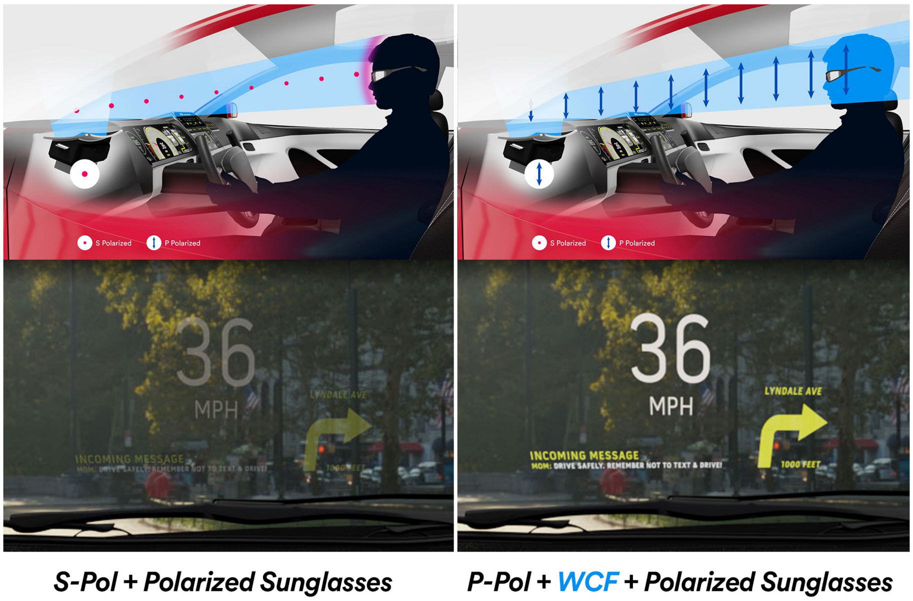

FIGURE 2 When a picture generating unit (PGU) projecting *P*-pol light is configured with a windshield combiner film (WCF) windshield, images are bright when seen through polarized sunglasses

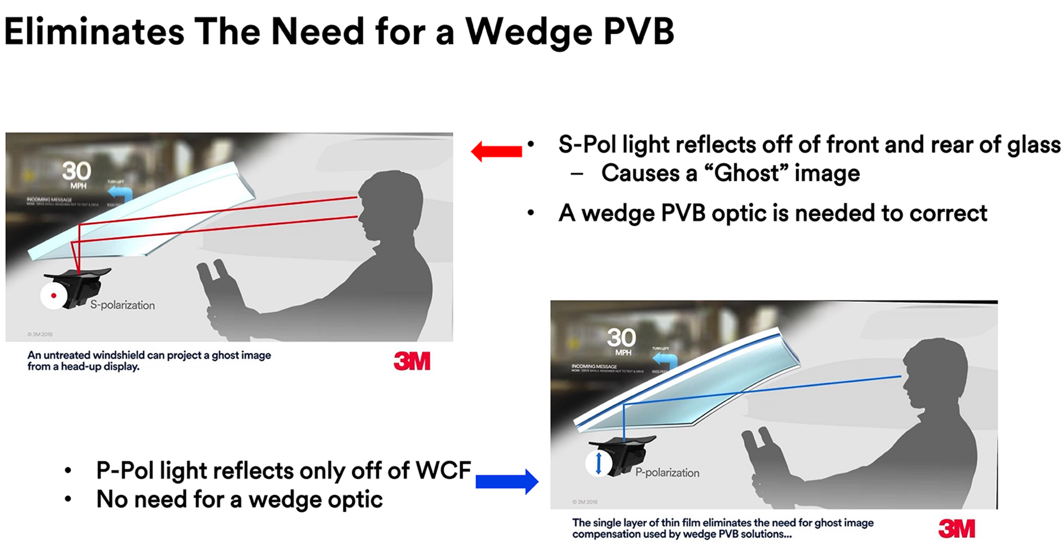

FIGURE 3 Windshield combiner film (WCF) eliminates the need for polyvinyl butryl (PVB) wedges to correct ghosting artifacts

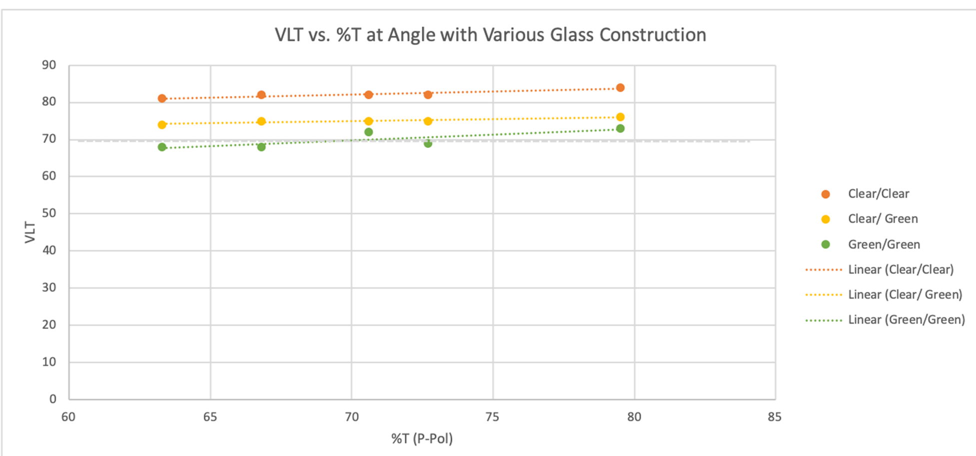

FIGURE 4 With windshield combiner film (WCF), display makers have multiple options for balancing visible light transmission (VLT) and reflectivity (%T *P*-pol) for various glass constructions

luminance than the image created by a current standard HUD (i.e., ~12,000–15,000 nits). As noted above, WCF is relatively insensitive to incident angle (though it is optimized for ~60°).

Additionally, WCF can be implemented with an asymmetrical windshield construction in which the adhesive on one side of the WCF is significantly thinner than the other (see Figure 5).

This geometry minimizes any film waviness caused during lamination and effectively eliminates noticeable associated reflected image distortion or "applesauce," which is a relatively low frequency (1–5 mm) wavy image distortion. The mechanical and environmental properties of this glazing geometry are currently being studied; initial results show a durability that is similar in performance to windshields with standard construction. Asymmetrical construction also helps to reduce any small (<1%) residual ghosting from *P*-pol reflection.

3.2 | IR rejection and cold mirror films

Several additional films address thermal management issues, which take on greater importance as manufacturers migrate toward increasingly compact HUDs with higher strength magnification and brighter images.[12–14] The use of a WCF, combined with a *P*-polarity-generating PGU, presents new avenues for reducing this thermal load.

The first is an IR rejection film, such as Ultra Clear Solar Film (UCSF), integrated into windshield fabrication. These films greatly reduce the transmission of light with wavelengths above 880 nm (Figure 6), thereby protecting PGUs; they also greatly reduce cabin solar thermal loading, which increases passenger comfort and reduces the energy needed for cabin cooling.

The use of windshield IR rejection is not a novel strategy, but it can be fraught with complications; in particular, windshield fabrication can be significantly more complicated when manufacturers integrate IR films with PVB wedge adhesives. However, because WCF eliminates the need for a PVB wedge adhesive to join both panes of glass, it allows for new approaches to windshield fabrication. Specifically, it allows a fairly straightforward integration of IR rejection film.

Other opportunities for thermal management can be found within the HUD unit. One solution is to replace conventional metalized cold mirrors with an advanced cold mirror film (CMF); this multilayer reflective polarizer film is an extraordinarily effective mirror, reflecting over 95% of the useful visible light (i.e., light with the orthogonal polarization) output from the LCD.

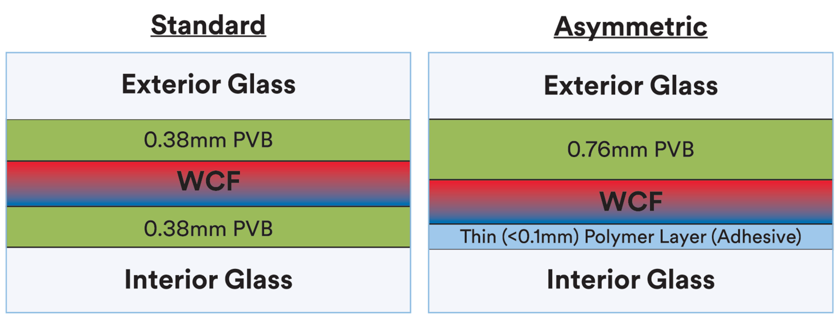

FIGURE 5 Glazing options with combiner film: asymmetrical adhesive layers retains safety and durability while improving visual quality. PVB, polyvinyl butyrl ; WCF, windshield combiner film

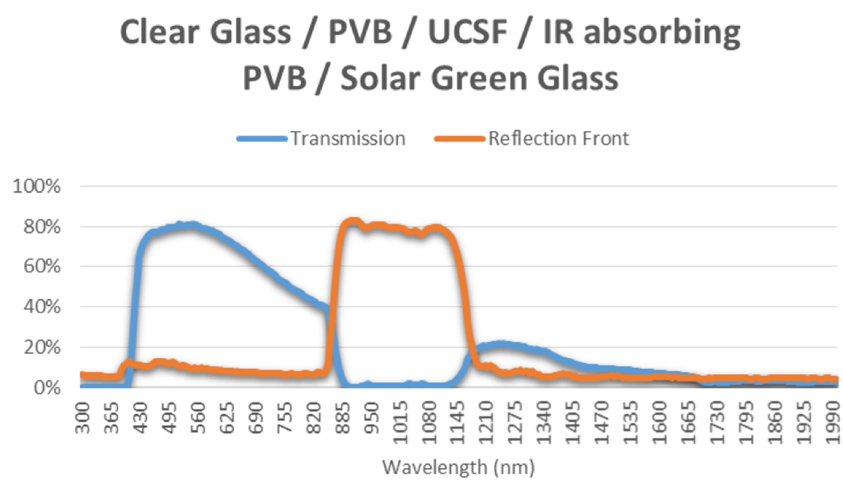

FIGURE 6 Dramatic reductions in infrared (IR) heat (achieved by IR rejection films configured with IR-absorbing polyvinyl butyrl [PVB]) minimizes solar energy impact on picture generating units (PGUs); this configuration also increases cabin comfort and reduces demand on air conditioning (AC) units

At the same time, it protects the PGU from solar infiltration by transmitting half of the sun's visible light and over 90% of near-IR (NIR) energy (Figure 7).

Depending on the HUD design, the cold mirror film can produce unwanted visual artifacts on the display. Specifically, as half of the visible light passes through the CMF, it can create interior reflections (also called stray light). For example, the light can reflect on screw heads or the contours of the casing. These stray light effects can be eliminated using a visible light absorptive layer behind the CMF. With the proper location and design of the visible light absorptive layer, the thermal benefits of CMF can be achieved without the concern of stray light.

Because the CMF is a polarized reflector, it can also tune the output polarization orientation for optimal image quality for skew angle light incident onto the windshield due to windshield curvature and high FOV HUDs. This issue of skewed light will become more significant with the rise of large FOV AR HUD. New research indicates that a slight rotation of the CMF can ameliorate some of the problems associated with skewed light by adjusting the output polarization; initial tests suggest that polarization can be altered within ±10% without losing more than 1%–3% luminance (incidentally, in windshields that do not employ WCF, the CMF can be rotated to optimize the mix of *S*-pol and *P*-pol light desired for a given HUD unit/windshield configuration).

3.3 | Other reflective polarizers

Other reflective polarizers can be used throughout the HUD to reduce solar energy and heat from the LCD panel. Applying a reflective polarizer to the dust cover (see Figure 8) will protect the PGU from the thermal impact of incident solar energy; applying a reflective polarizer to the PGU's LCD panel will reject solar and/or PGU heat loading and thereby reduce the temperature.

When applied in concert, these films can significantly reduce the heat to which the PGU is subjected. In one HUD example, PGU heat was reduced by as much as 5°C after approximately 20 min of simulated sunlight exposure simply by replacing the conventional cold

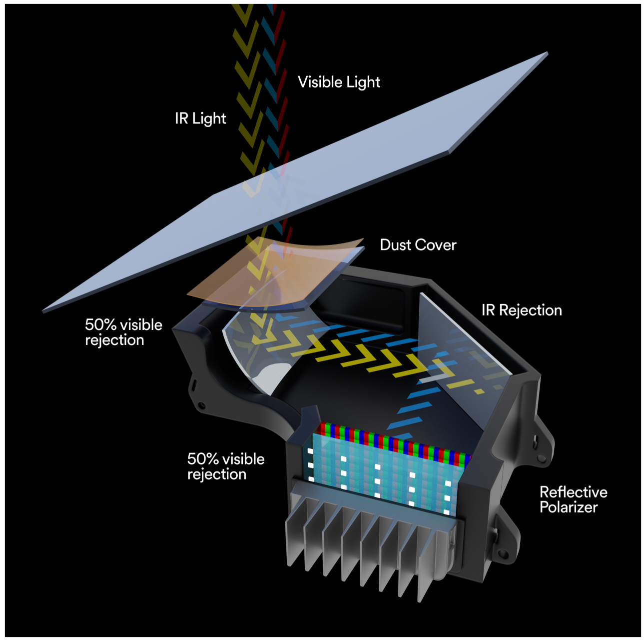

FIGURE 8 Integrating a reflective polarizer into the picture generating unit (PGU) dust cover can reduce visible light (and solar heat) infiltration by approximately 50%. IR, infrared

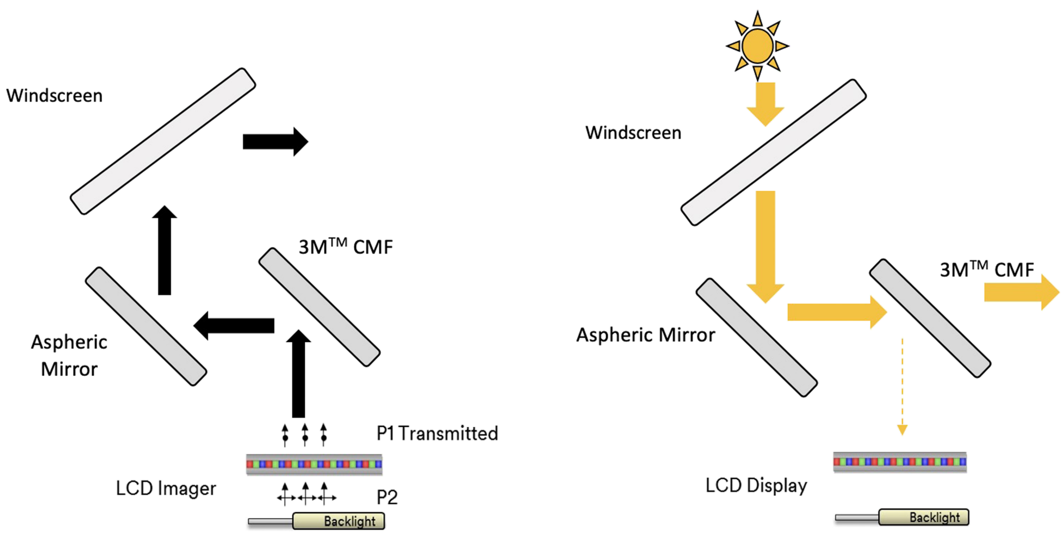

FIGURE 7 Cold mirror film (CMF) (based on reflective polarizer technology) enables efficient transfer of polarized light to the windshield head-up display (HUD) but allows only approximately 28% of solar irradiation to be reflected onto the liquid crystal display (LCD)

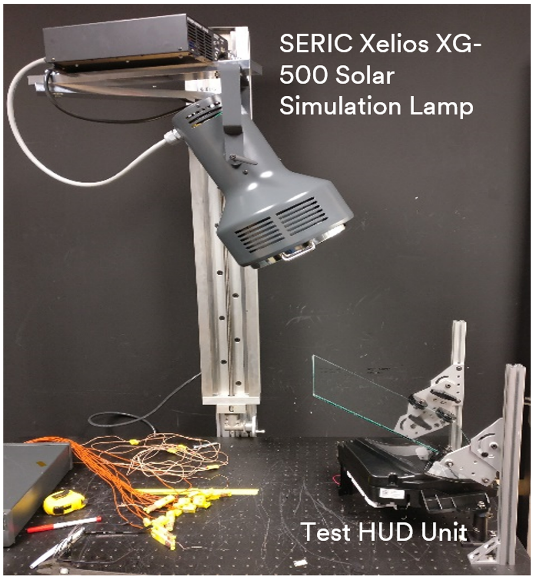

FIGURE 9 Experimental thermal measurement set-up to examine liquid crystal display (LCD) temperature reduction. HUD, head-up display

mirror with CMF (see Figure 9 for experimental setup*). A similar 5°C reduction was achieved by adding either a dust cover polarizer or a front LCD panel polarizer to the conventional cold mirror.

In this test case, the LCD temperature reduction can be doubled to approximately 10°C by combining 3M CMF with a single rear LCD panel polarizer or by combining the conventional cold mirror with two films (either a dust cover polarizer and a rear LCD panel or two LCD panel polarizers) (Figure 10). The first configuration, with one less component, is obviously simpler and easier to process.

3.4 | Other films for driver information display and center information display application

Other displays within the cabin can affect the AR HUD; managing those displays—again, as part of a whole-system approach—will ensure the optimal in driver safety and convenience. A good example of this are the multiple displays that comprise the driver information display (DID) and the center information display (CID), including back-up camera screens, maps (which can be displayed along with the HUDs turn-by-turn navigation), entertainment, and heating/cooling information. When these displays

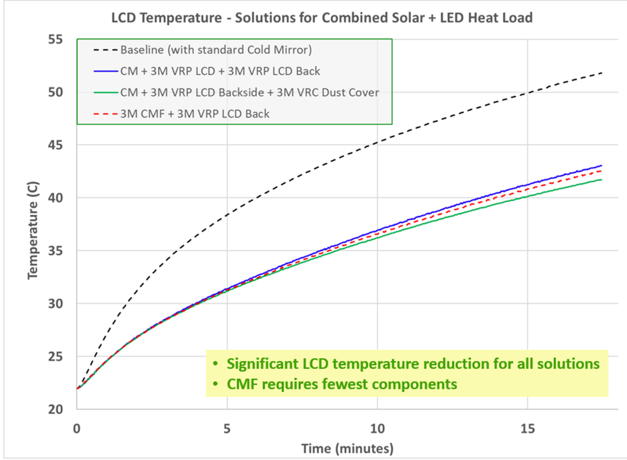

FIGURE 10 Liquid crystal display (LCD) temperature can be significantly reduced using several configurations; cold mirror film (CMF) and rear panel reflective polarizer achieve benefits with fewest components

appear in a brow-less dashboard, the resulting glare has the potential to reflect off the windshield at night (and make it more difficult for the driver to see the road).

The glare from the DID and CID can also interfere with the drivers' ability to read the AR HUD; this, in turn, can increase the need for AR HUD brightness, which in turn can affect heat and PGU durability. This glare can be effectively managed through the application of microreplicated louver films that direct light to the side (where the driver and passenger sit) and block it from the windshield—another example of the value of taking a holistic approach to the design of the cabin ecosystem.

Other improvements to the DID and CID can also affect the overall cabin ecosystem by improving efficiency and reducing heat. The use of a reflective polarizer film in these displays can increase display efficiency by as much 30%, thereby requiring less power (and generating less heat) while still achieving the brightness needed to surpass the ambient light during daylight hours. The reduction of heat in the DID and CID, as in the HUD PGU, will improve system durability.

4 | CONCLUSION

Vehicle displays, particularly large FOV AR HUDs, have seen impressive advancements in recent years. To continue this progress—and make AR HUDs commonplace in the not-distant future—display manufacturers using the most common HUD architecture will need to

*While the lamp used in the setup did have a spectrum similar to the sun, it was not collimated so it did not focus onto the LCD the way sunlight would. In a real-world (sun) situation, the temperature difference might be quite a bit higher.

adopt a holistic approach that addresses the interrelationship between key benefits (such as image brightness and quality) and key concerns (such as risks to unit durability from solar energy and the heat generated by the LCD panel).

In this paper, we have discussed how new WCFs can enable AR HUDs while also

- eliminating the need to PVB adhesive wedges in window construction,
- allowing display readability while wearing polarized sunglasses (when the display incorporates a *P*-pol PGU), and
- allowing an easier integration of IR rejection film.

The driver safety and convenience benefits of the AR HUD would not be possible, though, without other new films that can manage the solar energy and heat from the LCD panel. This thermal management can be effectively managed with a cold mirror film and reflective polarizers on the dust cover and the LCD panel. In addition, a microreplicated louver film can manage the potential glare from other displays within the cabin to remove distractions from windshield and window reflections, which can affect the demands on HUD performance.

All these films are commercially available with the exception of WCF, which will be launched within the next year.[15] This means that a holistic approach to HUD design using these tools is not only desirable but also practical.

REFERENCES

1. Normile, Brian. (May 14, 2020). Which cars have head-up displays for 2020? Retrieved from https://www.cars.com/articles/which-cars-have-head-up-displays-for-2020-421615/
2. Gitlin, Jonathan M. (July 10, 2020). Augmented reality heads-up displays for cars are finally a real thing. *Ars Technica.* Retrieved from https://arstechnica.com/cars/2020/07/augmented-reality-heads-up-displays-for-cars-are-finally-a-real-thing/
3. Continental head-up display with DMD technology goes into production for the first time with Lincoln. (November 14, 2017). https://www.continental.com/en/press/press-releases/2017-11-14-dmd-hud-104430
4. Cutting-edge technology powers Continental's augmented reality head-up display. (October 10, 2018). https://www.continental.com/en/press/press-releases/2018-10-10-waveguide-hud-147374
5. Jarrett DN. Cockpit Engineering Farnham, United Kingdom: Ashgate Pub; 2005. p. 189 ISBN 0–7546–1751-3. ISBN 9780754617518. Retrieved 2012-07-14.
6. Harrison AK. (1994) Head-up displays for automotive applications (Report No. UMTRI-94-10). Ann Arbor: The university of Michigan Transportation Research Institute.
7. Wheeler M. (2016) HUD systems: augmented reality is coming to your windshield. Photonics spectra. Available from: https://www.photonics.com/Article.aspx? AID=58298
8. Visteon. (2016) Displays, HUD and augmented reality, WardsAuto UX
9. Waldern J D, Grant A J, Popovich M M. (2018) DigiLens switchable Bragg grating waveguide optics for augmented reality applications. Proc. SPIE 10676, digital optics for immersive displays.
10. Kern TA. (2017) Optimization of head-up display systems. Automotive Visual & Display Technologies Europe. Automotive IQ. Krefeld, GR.
11. Hecht E. Optics 2nd ed. Reading, MA: Addison-Wesley Publishing Company. pp. 296–299.
12. Pankratz S. Study of thermal management solutions for head-up displays. SID Vehicle Display 25th Annual Symposium, Digest of Technical Papers, 2018.
13. VanDerlofske J, Pankratz S, Johnson M, Franey E New optical films for next generation AR head up displays (HUDs). SID Display Week Symposium 2019, Dige Tech Pap, (Vol. 50, No. 1, pp. 897-900).
14. Diepholz W, VanDerlofske J, Pankratz S. (2019) Strategies for eliminating incidental stray light in head-up displays. SID Vehicle Displays, Livonia, MI., Paper 4.2.
15. For technical data sheets and other information on 3M films for AR HUDs, please visit 3M's Head-Up Display Solutions website: https://www.3m.com/3M/en_US/oem-tier-us/applications/human-machine-interface-solutions/head-up-display/

AUTHOR BIOGRAPHIES

John Van Derlofske received his PhD in physics from the University of Alabama in Huntsville where his thesis work concentrated on illumination systems design. After graduation, he worked as head optical designer for Chrysler, developing automotive lighting and illumination systems. Van Derlofske spent the next 8 years at Rensselaer Polytechnic Institute heading the Transportation Lighting Group at the Lighting Research Center. His responsibilities included research, curriculum development, and teaching graduate-level courses in lighting technology and design. Over the course of his academic and professional careers, Van Derlofske has authored over 100 publications and given more than 75 presentations at national and international venues. Currently, Van Derlofske is a senior research specialist at 3M's Display Materials and Systems Division Laboratory where he works on the design, manufacturing, and application of light management products for the automotive HMI and sensor market to improve safety, comfort, and user experience.

Steve Pankratz received his PhD in physics from the University of Minnesota in Minneapolis where his thesis work focused on phase transitions and other properties of liquid crystals. Upon graduation, he worked at 3M in the Optical Systems Division on developing new light control films that make displays brighter, more efficient, thinner, and more durable. Pankratz holds six patents related to display enhancement and testing of optical film properties. He developed a course on the optics of these films and provided training at several 3M locations. Pankratz left 3M for a period of time to do nonprofit work overseas and then returned to 3M Display and Materials Systems Division. He is currently a product development specialist working on the design and application of optical films for both HUD and other displays and sensors for the automotive market.

In 2020, **Eileen Franey** received her Master of Business Administration from Duke University, after receiving her Bachelor of Science degree in Chemical Engineering from the University of Minnesota. She has been with 3M since 2013, serving as product engineer, project manager, and technical lead for new product development. As a senior application engineer in 3M's Display Materials and Systems Division, she has worked closely with customers to develop windshield and light management solutions, and managed competitive analysis of the automotive light management markets.

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