



Production of Head-Up Display windshield and its relation with the image quality

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ABSTRACT: Previously, car windshields served as a barrier against the wind or to prevent the driver from flying outside the vehicle in a collision. The windshield is therefore laminated and consists of two glasses and an intermediate layer consisting of the so-called polyvinyl butyral foil. The latest trend in car windshields is to consider the windshield as a display and project key information onto the windshield. Such glasses are called head-up displays. Various information such as car speed or route can be projected. The driver thus constantly maintains contact with the road, which increases driving safety. Head-Up Display quality is key to display information correctly without negative effects. Such a negative effect is if the displayed information is duplicated, which is called ghosting or double-image. This effect is undesirable and ranks first among the defects we detect in Head-Up Displays. The aim of this article is to compare different production technologies with a focus on the quality of HUD projection

and on the double-image occurrence. The production technology enabling optimal HUD image quality is discussed as well. The article deals with a summary of HUD production technologies, focusing on the most common defect that occurs in HUD windshields and which reduce the overall quality of the product. The article evaluates and summarizes the key findings from the perspective of the end customer, but also in terms of the production process. For the driver, as an end customer, it is a source of information according to which he can orient himself in the offer of car equipment. It can be useful for production or development people in terms of processability and process costs. At the same time, the benefits and negatives of using windshields with a Head-Up Display are discussed.

KEYWORDS: Head-Up Display windshield, Ghosting, Automotive, Augmented reality, PVB

1. INTRODUCTION OF HEAD-UP DISPLAYS

The car market is electrifying and, in general, there is an effort to increase driving safety for drivers, this can be achieved both by integrating above-standard automatic sensors into cars, but also by simplifying driving. One of the innovative systems is the windshield with a Head-Up Display [1]. The on-board integrated projector transmits a light signal via a mirror system to the windscreen. With this system, the driver sees key information displayed directly on the windshield and thus does not lose contact with the road. The Head-Up Display advantage stems from an improved situational awareness and the elimination of the need to look away from the road while driving [2]. This shortens the reaction time and gives the driver a better chance of reacting to driving obstacles, such as pedestrians, wild animals or others [3]. This is assumed to be the case because the speedometer at the driver's eye level allows continuous monitoring of the vehicle speed. The use of HUDs also seems to increase the overall quality of driving, including staying in traffic signs, and improving the flow of driving and navigation skills. Navigation information is also transmitted to the windscreen, so the driver does not have to watch the audio panel, which is usually out of the driver's view, and the driver must look away from the road to view the navigation information [4], [5]. The Head-Up Display is a solution to reduce the time and frequency when drivers look away from the traffic scene [6]. The windshield with a Head-Up Display is made by laminating two bent glasses with an intermediate core, which is most often polyvinyl

butyral. The interlayer often plays a key role, compensating for the angle of the windshield and preventing the driver from seeing the image in duplicate. The polyvinyl butyral intermediate layer has a certain angle, the so-called wedge angle, and thus performs a key function in the windshield with a Head-Up Display. The calculation of a suitable angle for a polyvinyl butyral film is crucial and is often based on complex mathematical simulations based on the shape of the glass and the required projection distance. The aim of the article is to discuss and compare the demands of windshield production with Head-Up Display compared to the demands of windshield production without Head-Up Display.

With HUD, the car's speed is displayed to the driver next to the speed limit directly on the windscreen, so that the driver can react and adjust the driving speed at any time (figure 1). On a complex traffic route, tracking GPS information becomes complicated, the HUD displays GPS in the driver's field of vision and offers stress-free driving conditions. The obvious advantage of HUD is a safer navigation. Even the fastest look down on the dashboard will distract the driver from the road, which is a safety risk, especially when driving at high speed [7]. With HUD, drivers have access to vital data in their field of vision and can focus where it is needed: on the road [8]. Augmented reality (AR) HUDs are the future: artificial intelligence-driven systems provide drivers not only with traditional vehicle data, but also with information about the car's wider surroundings, such as obstacles [9]. The major contributions of using windshield with Head-Up Display are:

- The road your field of view - regards to the Head-Up Display, the driver could concentrate more on the road, some of key information is displayed directly in front of him on the windshield. (Speed, GPS and others). The information from the display in the middle of the car is simply displayed on the windscreen instead of on the board, which can improve safety, because the data is displayed in the driver's field of vision when he looks ahead at the road.
- Safety – windshield with Head-Up Display contributes to reducing the risk of distractions. With HUD as the speed is displayed next to the speed limit directly in front of the driver. The speed limit is easily adjustable.
- Driving quality - following a complex traffic route, tracking GPS information becomes complicated; HUD displays GPS in the driver's field of vision offers stress-free driving conditions. With HUD, the driver is able to see and receive a call without taking your eyes off the road. On the other hand existing experiments have shown that receiving a call may cause an accident because it delays visual information processing by the driver. This benefit of Head-Up windshield should therefore be taken in quotation marks [10-11].



Figure 1. Head-Up Display principle of the projection.

2. GHOSTING PHENOMENA

The key parameter of the windscreen with Head-Up Display is the image quality. Glass must be designed and manufactured in such a way that a double image is not formed. A double image is formed when light is reflected from the outer or inner surface of the glass. By default, polyvinyl butyral (PVB) interlayers with a linearly or non-linearly varying PVB thickness across the face joint are used to reduce the occurrence of a double image. The resulting wedge angle allows reflections to overlap and the image has not been duplicated. This technique works well for a certain driver's position, as the driver moves up or down with the seat, the image quality usually deteriorates. As a rule, the resulting image is a combination of different driver sizes [12].



Figure 2. Double image on the windshield.

Ghosting can be caused by uneven glass thickness or PVB in place of the Head-Up Display. The key element for minimizing ghosting in the area of the Head-Up Display is the shape of the

outer and inner glass and their parallelism, and in the second place the stability of the wedge angle PVB film. From this point of view, PVB production seems to be a critical parameter. All variants using the principle of creating a wedge angle with the help of PVB are sensitive to the processing of PVB film. Suppliers can supply material that has already created a wedge angle, eliminating the need for the windshield processor to create a wedge angle on the cutting line. Each operation after winding the PVB into a roll on the part of the intermediate layer manufacturer on the extrusion line is sensitive to changes in the thickness of the PVB and thus to changes in the wedge angle. The thickness changes can occur in the vertical direction or in the horizontal direction, whereby vertical or horizontal ghosting is created. The key influence is therefore the process of unwinding the material from the roll and cutting the material. During unwinding, the material is reheated above the glass transition temperature of the PVB, which leads to changes in the thickness of the material. This process can change the wedge angle [13]. Ghosting can be suppressed by modern windshield technology with Head-Up Display.

3. HEAD-UP DISPLAY CONFIGURATION AND DESIGN

The windshield is designed using sophisticated mathematical simulation tools. Emphasis is placed on both the quality of the glass used to make the windshields with the Head-Up Display (HUD) and the quality of the PVB film, which is the intermediate layer responsible for laminating the two glass panes.

Today's most widely used commercial HUDs use optics to generate a virtual image on the front of the windshield. The HUD projection unit consists of a radiation source, the so-called image generating unit with the display at the top. Since the image is generated light goes to the fold mirror. The advantage of the fold mirror is the ability to reduce the package size. The light then progresses to rotatable mirrors, called aspherical mirrors. Aspherical mirrors allow image magnification to get a certain projection distance of the virtual image. These aspherical mirrors partial corrects the distortion coming from the windshield as the windshield is bent. The target is to get the rectangular image at the end. The capability to rotate the image allows to the driver to adapt the optimal Head-Up Display image based on the driver's height and sitting position in the car. The light is then reflected by the windshield and it is coming to the driver's eye. As the reflection of the light takes place on the outer and inner glass, a double image is created as standard. For this reason, the glass made for the Head-Up Display has a certain angle, called the wedge angle, which allows the images to overlap so that no double image but only one image is observed. On the surface of the projection unit there is a so-called light trap and glare trap, which has the task of reflecting the radiant radiation into the black plastic material, thus preventing the reflection of solar radiation on this surface, which could dazzle the driver (figure 3) [14].

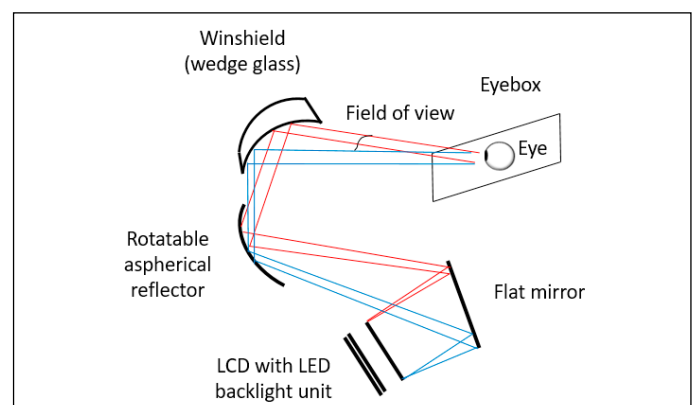


Figure 3. Head-Up Display principle of the projection.

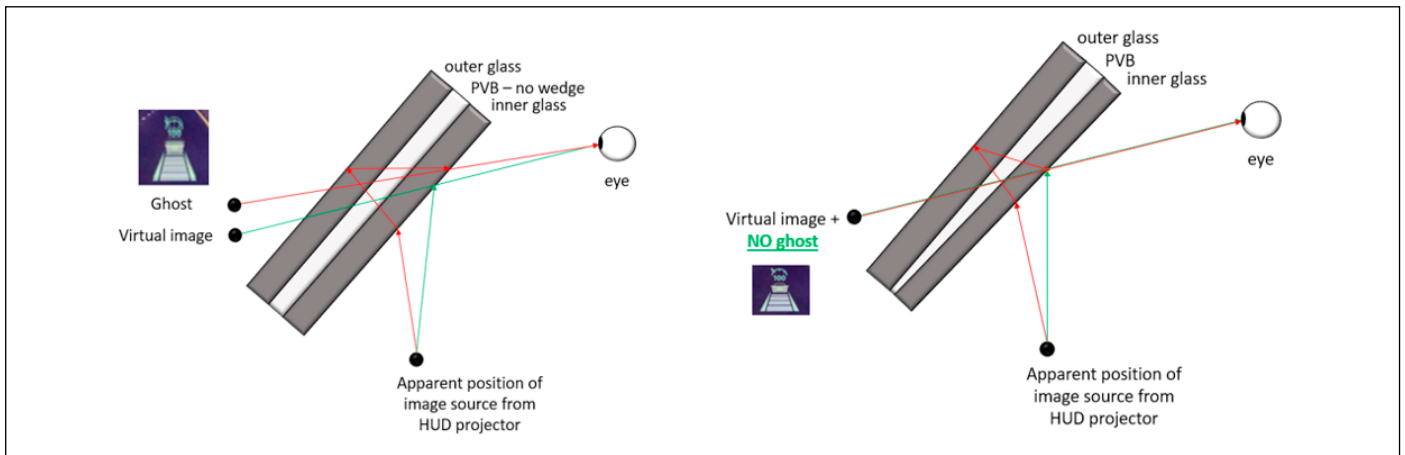


Figure 4. Principle of the double image creation.

4. PRINCIPLE OF DOUBLE IMAGE

The principle of the wedge PVB function is to overlap the primary and secondary images, thus preventing the occurrence of a defect, the so-called double image. Absolute double image prevention is difficult to prevent throughout the screen, but the goal is to minimize the occurrence of this defect. Maximum acceptance limits for the occurrence of a double image on the windshield are often addressed because different height drivers look at the projected image from a different angle, with the result that different height drivers perceive different double image intensities (Figure 4) [15].

5. PRODUCTION OF WINDSHIELD WITH HEAD-UP DISPLAY

The windscreen with Head-Up Display consists of two outer panes that are laminated together using a polyvinyl butyral interlayer. Polyvinyl butyral provides primarily a safety function, but in the case of windshields with a Head-Up Display, it also ensures optimal functionality of the glass with a Head-Up Display. In the case of glasses with a Head-Up Display, the PVB intermediate layer has a certain wedge (Figure 5) [16-17].

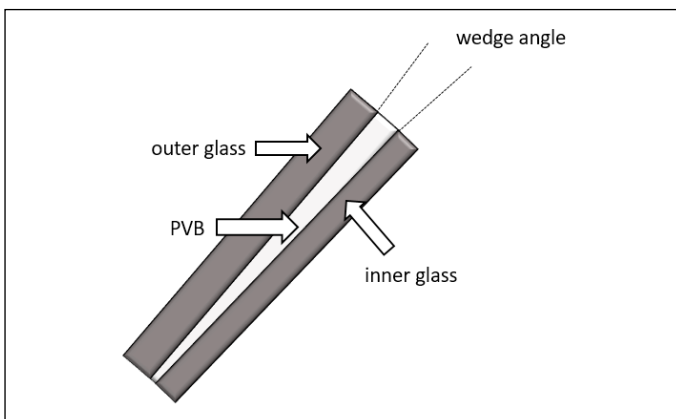


Figure 5. Composition of the windshield with Head-Up Display function.

The windscreen with the Head-Up Display function consists of two glasses, an inner and an outer glass, and an interlayer of polyvinyl butyral, which connects the glasses together.

6. PRODUCTION OF POLYVINYL BUTYRAL LAYER

Polyvinyl butyral is one of the polymers, specifically thermoplastics. The thermoplastic material is able to soften

when heated and harden again after cooling. And this process is repeatable. PVB film is produced by extrusion of synthesized polyvinyl butyral, which is mixed with plasticizers and other additives. The homogenized mixture with polymers and additives is fed to a compression screw. The PVB extrusion process takes place through a mold of defined shape. The material is then wound on rolls and is ready for further processing (figure 6) [18].

PVB is unwound from the roll on the cutting line in a clean room. PVB is stretched, shaped and cut into PVB sheets. PVB sheets are assembled with bent glass sheets in a lay up room in the process called assembly (figure 7) [19].

7. PRODUCTION OF GLASS SHEETS

Glass panes are made on a float line by floating the glass over a tin bath. Different compositions and colors of glass can be used to make glass with a Head-Up Display. We most often talk about the use of soda-lime-calcium glass, either clear glass or tinted glass. Emphasis is placed on glass quality to avoid image distortion when projected onto the windshield. The glass is then cut on a cutting line into shapes according to the windshield. The glass is ground and washed, then a black print is applied on it, which has a predominantly aesthetic function, but can also be used to project information on the windscreen. In the next step, the glass is bent into the desired shape, either in pairs or each glass using different bending techniques separately. The most common windshield bending technologies include gravity bending of the windshield, or bending using a press, so-called curvature or double-curvature bending, based on whether the glass is pressed from one or both sides [20].

8. LAMINATION OF WINDSHIELD AND FURTHER PROCESSING OF THE WINDSHIELD

After bending the glasses, the glasses are laminated with a PVB interlayer [21]. The inner and outer glass with polyvinyl butyral foil is pressed either by passing it between two rollers, so-called nipper roller, or by means of vacuum profiles, or by using bags into which the glass is closed and a certain temperature and pressure are applied to them. The pre-pressed glass enters the autoclave, where the residual air is sucked out [20-21]. The glass is checked for defects and then goes to another process, where other parts are applied to the glass, such as polyurethane profiles, which are glued to the glass with the help of polyurethane adhesives [22-23].

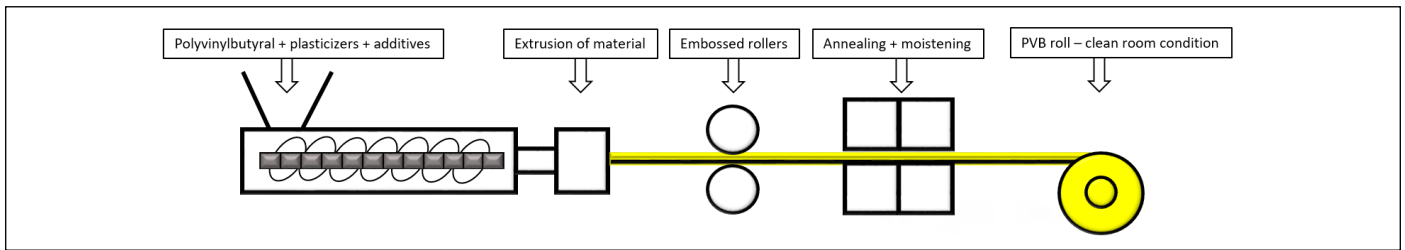


Figure 6. PVB extrusion line scheme.

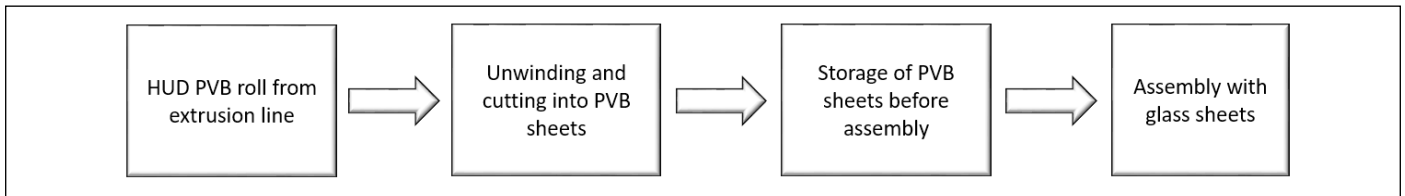


Figure 7. Process steps of PVB material processing.

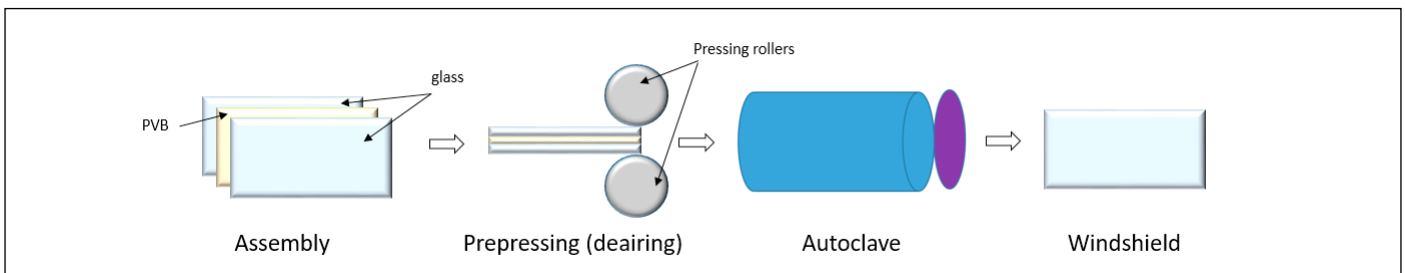


Figure 8. Lamination process of windshield with Head-Up Display

9. DIFFERENT OPTIONS HOW TO PROCESS HEAD-UP DISPLAY WINDSHIELD

The size of the wedge angle depends, among other things, on the geometry of the laminated windscreen and the design of the Head-Up Display. There are several options for manufacturing a windshield with a Head-Up Display. The most common way is to use a HUD PVB with a non-uniform thickness profile.

9.1 Head-Up Display using HUD PVB

The basic principle of creating a wedge angle in PVB film is the process of extruding the material using a wedge-shaped extrusion press on an extrusion line. This wedge PVB is then laminated with the inner and outer carbon glass. The result is a glass with an uneven thickness, where the HUD PVB foil between the glasses ensures an uneven thickness [24].

9.2 Head-Up Display using PVB with uniform thickness that is stretched and shaped on the stretch line

An alternative principle of glass production with Head-Up Display is again the use of wedge PVB foil. The input material is PVB with uniform thickness. The thickness profile of the PVB film is subsequently formed on the tension line during the production of the PVB film. An unwound flat thermoplastic film of uniform thickness from a PVB roll is stretched and shaped on a stretching line. The PVB cylinder then enters the zone where it is heated and comes into contact with various heating cylinders. The PVB is tensioned between two pressure rollers and then processed by the wedge profile roller, where an uneven thickness is formed on the bottom and top of the PVB film. At this point, the PVB is shaped so that the profile of the PVB board, which is cut out of the PVB film in the next step, perfectly matches the shape of the glass [25].

9.3 Head-Up Display using coated glass

Another way to make a windshield with a Head-Up Display is to use a coating on the glass. In this case, it is not necessary to use wedge PVB film for glass lamination (Figure 9). Coating is sputtered on the glass sheets using magnetron sputtering process. Sputtering is the removal of material from a solid target by energetic ion bombardment. The ions come from a magnetically confined plasma created above the target surface. Sputter deposition is a process of coating a substrate with the material removed from a target by sputtering [26-27].

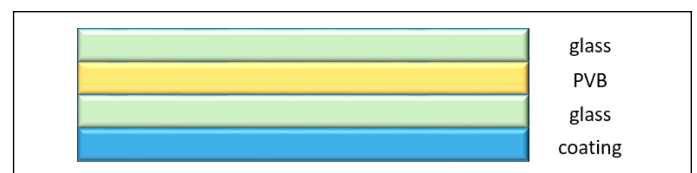


Figure 9. Composition of the windshield with Head-Up Display function.

9.4 Head-Up Display using PET film

Another method of manufacturing a windshield with a Head-Up Display introduces a special PET film with a metal coating, which prevents the formation of a double image, but this production is demanding and PET film with a metal surface is difficult to form. PET film often has to be combined with other interlayers to provide other functions, such as the acoustic properties of glass. Then it is necessary to combine the PET film with the polyvinyl butyral film [28].

9.5 Holographic Display using holographic optical elements

The last introduced technique of Head-Up Display windshield is a technique using the holographic imaging using holo-

graphic optical elements (HOE). HOE is an optical component (mirror, lens, directional diffuser, etc.) that produces holographic images using principles of diffraction. The use of HOE allows you to increase FOV. The technique again uses a picture generating unit (PGU). The use of HOE optics ensures the achievement of a high quality image in the entire field of view for the eye box (figure 10). If the Head-Up Display windscreen uses holography projection, there is no need to use a HUD PVB, which is a huge advantage for Head-Up Display windscreen manufacturers, as they can use a standard thickness PVB film that is cheaper and less sensitive to processing [29-30].

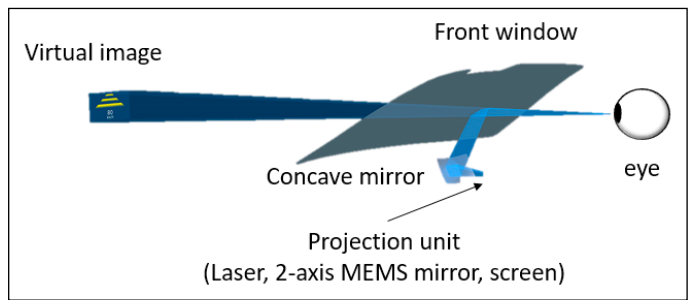


Figure 10. Composition of the windshield with Head-Up Display function using LiDAR.

9.6 Holographic Display using LiDAR

A holographic automotive Head-Up Display has been developed to project 2D and 3D ultra-high resolution (UHD) images using LiDAR data in the driver's field of vision. Data from LiDAR is converted to generated holograms (CGH) using a computer. A Helium-Neon laser and a UHD surround light modulator are used for the reconstruction. 3D holograms are observed floating as an image of ghosts at a variable focal length with a concave lens and a digital Fresnel lens within the CGH. LiDAR is a remote sensing method that uses a laser pulse to measure the distance between a scanner and an object (figure 11). The LiDAR data is then combined with the cloud data and the result is a 3D model. Various cloud data are processed using algorithms to identify and extract various targeted objects. The technology aims to increase traffic safety by alerting the driver to potential dangers by being able to see obstacles through. With LiDAR, we can create high-quality ultra-HUD holographic images of road objects with images that appear directly in the driver's field of vision on the windshield. This is in contrast to standard HUD windshields, which project a 2D image. Using LiDAR, real objects are presented in panoramic 3D projections [31-33].

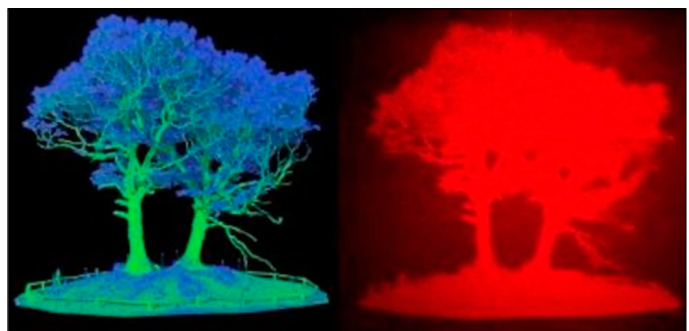


Figure 11. Left: an image of a tree based on LiDAR data. Right: the same image converted to a hologram.

9.7 Comparison of different production technologies and its effect on HUD projection quality

From the point of view of a windshield manufacturer with an implemented HUD display, we distinguish according to the

complexity of various options for the production of a windshield with a HUD. As a rule, variants that seem to be cheaper do not always show image stability, while solutions that are more expensive avoid unwanted duplicate images and also connect the windshield to virtual reality. From the manufacturer's point of view, it seems to be the most attractive variant that uses PVB stretching solutions (point 9.2) in the process that seems to be the least expensive, but this variant is only suitable for long projection distances, i.e. with small wedge angles. The greater the projection distance, the lower the wedge angle.

In the case of shorter projection distances, such as 2.5 meters, the wedge angle PVB has to be higher, which means that the wedge angle has to be created either by the HUD PVB supplier on the extrusion line (variant 9.1) or by other materials such as PET foil (variant 9.4) or using a coating (variant 9.3). To display higher projection distances, it is necessary to use variants with HUD PVB (9.1), with coating (9.3), or using holography (9.5, 9.6) (table 1).

Option	Producer of HUD windshield	
	Advantage	Disadvantage
Head-Up Display using HUD PVB	Wedge angle created on the extrusion line --> not necessary to shape PVB	High cost of HUD PVB
Head-Up Display using PVB with uniform thickness that is stretched and shaped on the stretch line	Lower cost	Necessity to shape PVB --> difficult processing of PVB to achieve correct wedge angle with enough capability
Head-Up Display using coated glass	Not necessity to use HUD PVB	Necessity to overcoat the raw glass
Head-Up Display using PET film	Not necessity to use HUD PVB	Necessity to use the PET film and PVB in combination
Holographic Display using holographic optical elements	Market seeking for it	Complex production
Holographic Display using LiDAR	Market seeking for it	Complex production

Tab. 1 Comparison of different production variants from the producer point of view

Image quality and price are important for the final customer. From the point of view of quality, the most optimal variant seems to be the variant that uses coating on glass, or uses holography. All film variants are risky in that they are production-intensive and require production under strict quality control to avoid double-image formation. The films are sensitive to changes in thickness during processing, which can result in a double image. There are not enough resources to compare the price to compare, but only based on the complexity of production, we estimate the use of coating on glass as the optimal option, which allows the use of standard PVB thickness and no need to deal with creating a wedge angle (table 2).

DISCUSSION

10.1 Hud quality

HUD technology is more advanced, the market is relatively stable [34]. In many respects, the Head-Up Display is beneficial and increases driving safety [35]. The main benefits include that the driver maintains and does not lose contact with the road in order to look at the current speed, notifica-

Option	Customer	
	Advantage	Disadvantage
Head-Up Display using HUD PVB	Ghosting level low + augmented reality	Higher cost
Head-Up Display using PVB with uniform thickness that is stretched and shaped on the stretch line	Ghosting level low If produced correctly	Ghosting level could be high
Head-Up Display using coated glass	Ghosting level low + augmented reality	x
Head-Up Display using PET film	Ghosting level low If produced correctly	Ghosting level could be high
Holographic Display using holographic optical elements	Ghosting level low + augmented reality	Higher cost
Holographic Display using LiDAR	Ghosting level low + augmented reality	Higher cost

Tab. 2 Comparison of different production variants from the producer point of view

tions on the infotainment, or information from GPS, as to where to turn, or how long it should take. The production of glass is demanding and most often uses uneven thickness of the intermediate layer of PVB film, which prevents the driver from seeing the image in duplicate. However, the given variant does not allow to get rid of the completely secondary image, it is a compromise between individual driver heights, if the driver is otherwise high, it is necessary to take into account the Head-Up Display, but not always and not for all driver heights the image and its quality is acceptable.

We are talking about the maximum achieved image quality that can be achieved with this variant. This variant is also problematic in that if the driver wears sunglasses, the projection disappears. For this reason, other options are being considered in the industry that negate the double image and allow a perfect image without duplication.

The HUDs is offered by many of car manufacturers (Mercedes, BMW, and Audi) are all Head-Up Displays with augmented reality. There is only a limited amount of companies offering smart holographic Head-Up Displays with a holographic projection. We have several augmented reality dashboard Head-Up Displays (lower left quadrant) in the aftermarket and from OEMs (upper right quadrant). BMW showed that they are working on holographic dashboard Head-Up Display windshield [36].

Recent technologies include the use of coating on glass, which blocks some polarization of light and allows the driver to reduce the intensity of the secondary image to a minimum. This variant most often uses the so-called p-polarization, which allows the driver to see the Head-Up projection even when wearing sunglasses

Manufacturers of windshields mostly prefer to use the glass with coating from several reasons. The main reason is that the production of wedge PVB is very expensive [9]. Another reason is that further processing of wedge PVB can be quite tricky since you have to secure the wedge angle in order to negate double image appearance. But you have to still unwind PVB from the roll, cut it to PVB sheets and laminate it with the windshield. All of these operations may cause the change of the wedge angle therefore the processes must be well designed in order to avoid undesirable change of the wedge angle in any of these processing steps [13].

Ghosting is mainly caused by the uneven thickness profile of the PVB interlayer, which in the case of coating we will close, as we will use a foil with a uniform thickness. There is no need to use or produce PVB with a certain wedge angle. Coated glass can be used for long projection distances, it also allows the image to be projected onto the entire windshield and there is no need to define HUD zones in which it is necessary to move when projecting the image. Coated glass will also allow the use of technologies such as LiDAR or others that enable virtual reality. If the sensors detect an obstacle in the way, the holography of the image will allow the obstacle to be highlighted or the vehicle to be stopped.

Parameter	Coating	Wedge PVB
Size of projected image	Full windshield	HUD window (550x280 or less)
Projection distance	High	High
Virtual reality	Yes	Yes
Ghosting level	Low	Could be high
Glass production complexity	Complex	Complex
PVB production complexity	Easy	Complex

Tab. 3 Coated glass vs. wedge PVB solution.

10.2 Safety aspect

The Head-Up Display, i.e. the device that projects important information directly in front of the driver, is still a luxurious element, although it is offered year after year in cheaper models. Its main benefit is users greater security. There are several advantages of windshield with Head-Up Display like:

1. It shows the driver all kinds of key information that the driver usually had to look for on different dials. Today's glasses with HUD, which are on the market will allow use of navigation via Bluetooth and GPS.
2. The projected data does not always distract the driver, as mobile phones or dashboard controls may do [37,12].
3. Eyes sharpen much faster when you switch from the road to the projected screen [38].
4. HUD displays are not very large and they can be easily implemented in a car with all the controls [3].

There are several disadvantages of windshield with Head-Up Displays like:

1. Voice or flashing text could be distracting.
2. It may be less visible during the day in the sun.
3. May not be visible with sunglasses.

SUMMARY

Head-Up Display windscreens may increase driving safety by allowing key information to be projected directly into the driver's field of vision although there is no study to support this claim. There are advantages and disadvantages of windshields with a Head-Up Display, but the positives still outweigh the negatives. The ability to maintain constant contact with the road could be potentially a feature and an advantage of windshields with a Head-Up Display. There are several ways of producing a windshield with a Head-Up Display, while different production methods allow to achieve different levels of ghosting, i.e. a negative effect, the so-called

double image, which arises if the primary and secondary images do not overlap.

The windshield with Head-Up Display is made by laminating the inner and outer bent glass with an interlayer, most often of polyvinyl butyral. The projection takes place using a so-called image generation unit, which projects information on the windshield through a system of mirrors. The problem with projection is a defect called double image. There are several ways to get rid of a double image, for example by using a wedge PVB film or by coating a glass or laminating a metallized PET film. The use of a coating that prevents the formation of a double image seems to be the most effective. Variants using wedge foil or polarizing foil are highly sensitive to processing so that the wedge of the foil is not damaged and thus a double image is formed.

The latest trend in Head-Up Displays is holographic projection, such as LiDAR. Using LiDAR, real objects are presented in panoramic 3D projections. The goal of the technology is to increase traffic safety by alerting drivers to potential dangers by being able to see obstacles through. Using LiDAR, we can create holographic images of objects with images that appear in the driver's field of vision.

The contribution of this article is to introduce the issue of using glass with head-up displays in the automotive industry. It introduces the issue of the production of such glass and allows drivers to find the benefits of using glass with Head-Up Displays and informs about the negatives of using such glass. It shows possible obstacles and defects that the driver may find when operating the windshield with a head-up display. It explains the issue of ghosting, which is generally unfamiliar to drivers. The driver still has a choice whether to buy a glass with a head-up display or not. It is up to the driver to decide whether he considers a car's windscreen with a head-up display to be an advantage or a disadvantage. This article describes the advantages and disadvantages of the windshield with Head-Up Display and approaches the issue of Head-Up Displays. At the same time, it reports on the production of the windscreen with the Head-Up Display and discusses the most common defect on the windscreens with the Head-Up Display, double image and discusses the possibility of preventing this defect.

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