Application Report
DLPA099–December 2018

Estimating Mechanical Volume of an Augmented Reality Head-Up Display System

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ABSTRACT

This application report explains the theory and mathematics behind one method of volume estimation for Augmented Reality (AR) Head-Up Display (HUD) systems. Automotive manufacturers and system suppliers can use this as a first order approximation of mechanical volume and as a tool to evaluate system tradeoffs. This application report should be paired with the AR HUD Volume Estimation Calculator to quickly estimate system volume for an AR HUD using the DLP3030-Q1 or DLP5530-Q1 automotive qualified chipsets.

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1 Introduction

As head-up display (HUD) parameters such as field of view (FOV), eyebox size, and virtual image distance (VID) increase, the physical volume of the HUD system must also increase. For large HUDs, this volume can approach 15 - 20 liters, which becomes the limiting factor for integration into the dashboard of a car. Proper care must be taken to define HUD specifications to maintain a reasonable volume for the desired application. This document details the calculations needed to estimate the overall volume of a HUD system for given parameters.

2 Head-Up Display Overview

A HUD system consists of three main subsystems: an imaging plane, reflective optics, and a combiner element. A HUD based on TI DLP® technology has an imaging plane created by a DLP projector and optical diffuser. This combination of projector and diffuser plane is called a picture generation unit (PGU). The reflective HUD mirror optics include one or two powered mirrors that prepare and magnify the image for viewing within the driver's viewing plane, or eyebox. The combiner element can be either a specialized glass or plastic optical element or simply the uncoated automobile windshield.

The source of the HUD image is created on the diffuser by the DLP projector. This image is magnified and reflected onto the windshield by the powered HUD mirrors. The light then reflects off the windshield and into the eyebox, as seen in Figure 1.

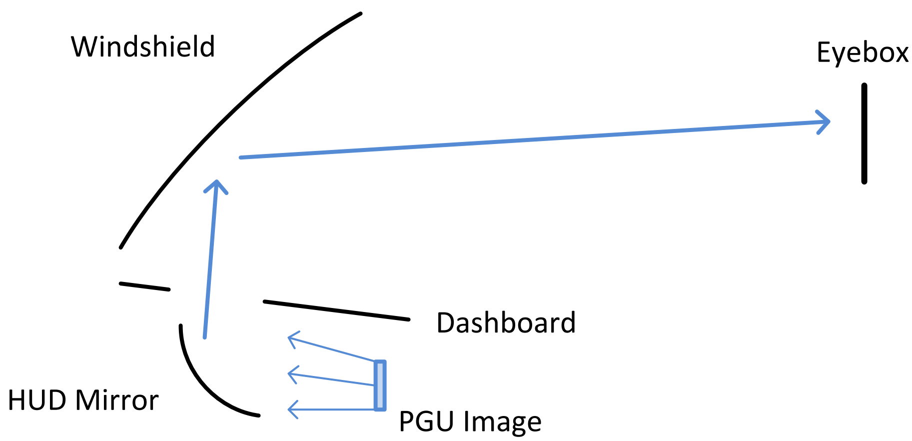

Figure 1. Typical HUD layout

The volume of a HUD consists of the enclosed space between the PGU and the primary mirror. This enclosure will sit below the dashboard of the car and must have enough room to fit behind the steering column and above the frame of the car. Often, other components like HVAC ducts and wiring bundles also share this dashboard space. HUD volume must be accounted for early in the vehicle design process to allow adequate space.

3 Primary Parameters Affecting Volume

An AR HUD system has three main parameters that affect overall volume:

- Field of view
- Eyebox size
- Virtual image distance

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All three of these parameters determine the size of the largest mirror inside the HUD. This mirror is the largest single component of the HUD optics and serves as a starting point for defining the shape of the HUD and the overall volume. The total volume is most sensitive to increases in the vertical direction through changes in vertical field of view. Eyebox height also increases overall volume more than equivalent changes in horizontal directions.

Other parameters such as mirror tilt angle, image magnification, and distance from the eyebox to the mirror also have an effect on the volume of the HUD, but these parameters are often fixed by the layout of the vehicle or are limited by manufacturing capabilities.

4 Estimating the Size of the HUD Mirror

The volume of a HUD is strongly influenced by the size of the largest HUD mirror which we call the primary mirror in the HUD design. This mirror will be located just under the glare trap at the dashboard level. Light rays leaving this mirror travel to and reflect off the bare glass surfaces of the windshield and then travel to the eyebox. The dimensions of the primary mirror can be estimated only with knowledge of the HUD design parameters.

The size of the HUD mirror is estimated using geometry given the parameters of:

- Virtual image distance (L_{VID})
- Eyebox size
- Magnification from real image to virtual image
- Total optical path distance from eyebox to the HUD mirror ($L_{M\text{-}EB}$)
- Horizontal and vertical field of view (HFOV and VFOV)
- Obliquity angle of the primary mirror

4.1 Size of the Virtual Image and Image Screen Calculations

The size of the virtual image can be calculated for a given FOV and VID.

$$Virtual\ \ Image\ \ Width = W_{VI} = 2 \times \tan\left(\frac{HFOV}{2}\right) \times L_{VID} \tag{1}$$

$$Virtual\ \ Image\ \ Height = H_{VI} = 2 \times \tan\left(\frac{VFOV}{2}\right) \times L_{VID} \tag{2}$$

The required screen image size can then be calculated by dividing the virtual image dimensions by the system image magnification.

$$Screen\ \ Image\ \ Width = W_{screen} = \frac{W_{VI}}{Magnification} \tag{3}$$

$$Screen\ \ Image\ \ Height = H_{screen} = \frac{H_{VI}}{Magnification} \tag{4}$$

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4.2 Primary Mirror Size vs VID

The size of the primary mirror will increase as a function of virtual image distance. Most of the increase is found in the first 10 m of virtual image distance. For a VID greater than 10 m, the mirror size increases very slowly.

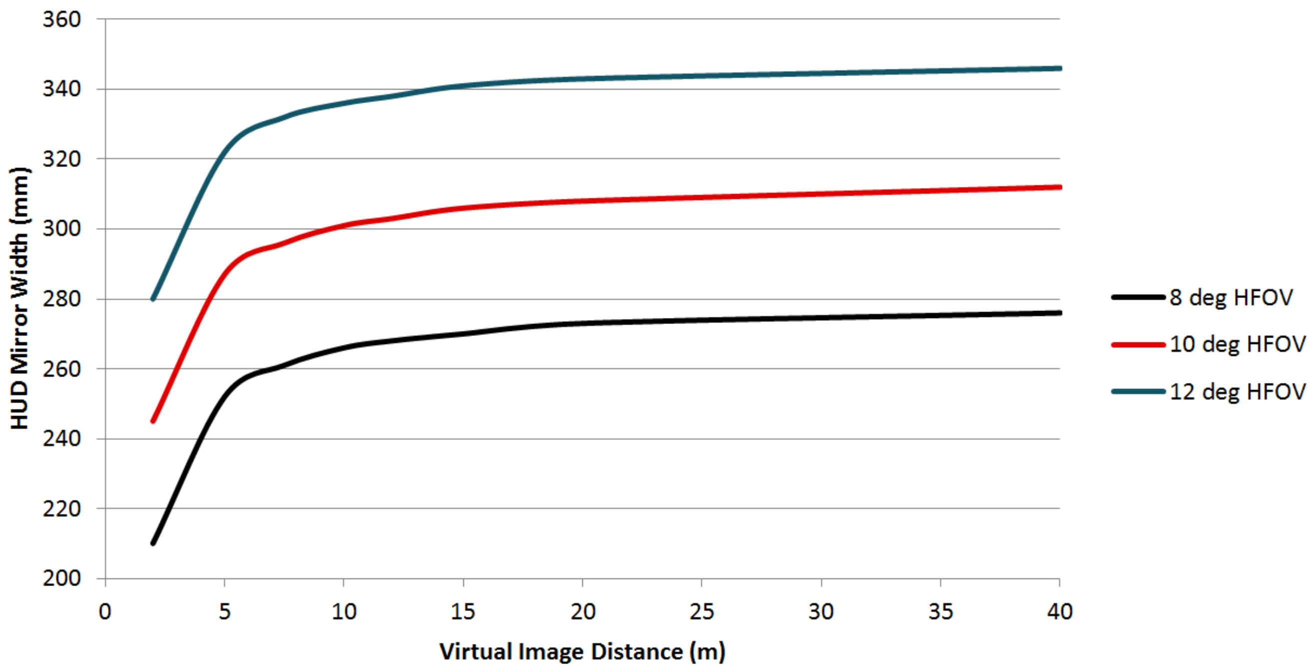

Figure 2. HUD mirror width vs VID

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4.3 Primary Mirror Width Calculations

The spatial relationship between eyebox size, virtual image size, and mirror size is shown in Figure 3 in this top down view of the geometry.

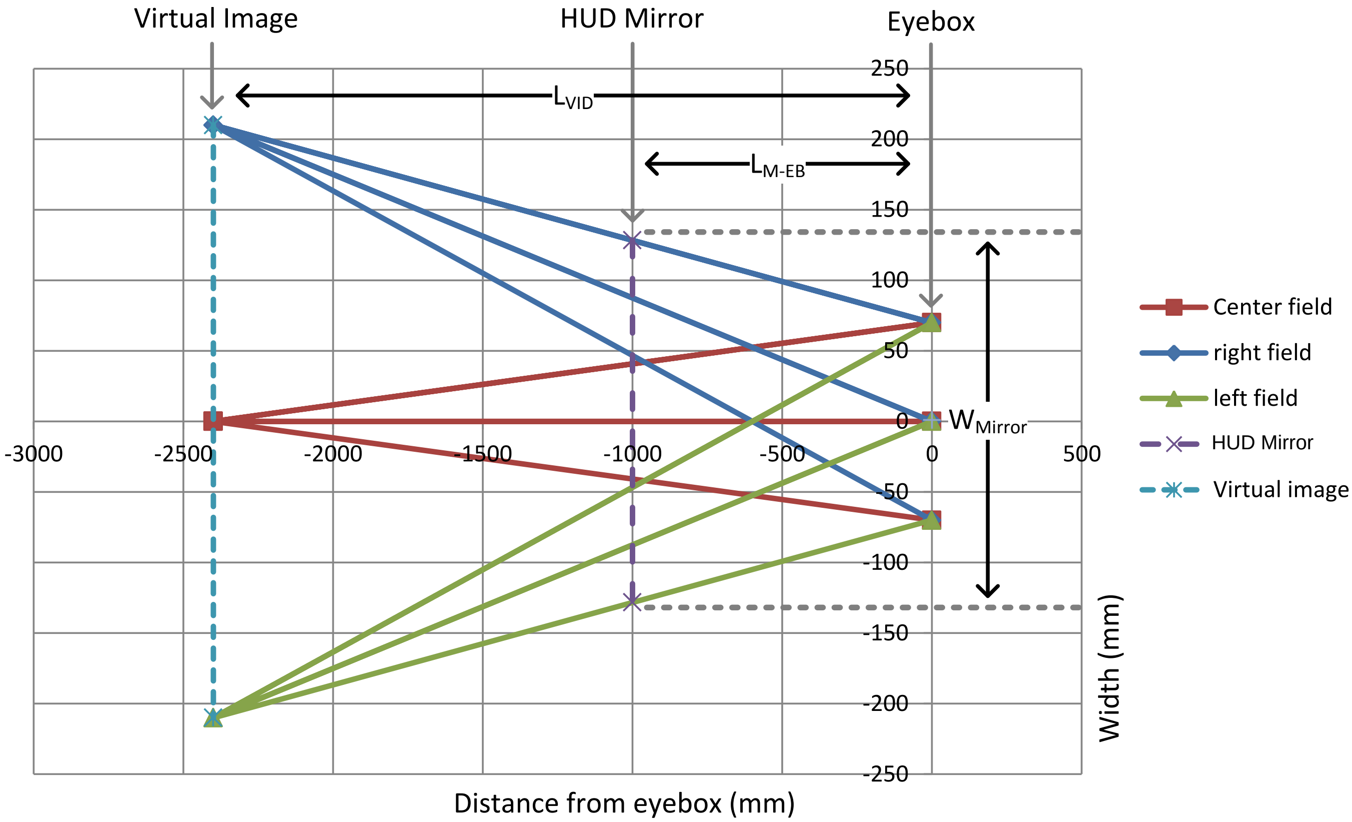

Figure 3. Width calculation of the primary mirror

The primary mirror width is calculated using geometry once the total distance from the primary mirror to the eyebox is known or estimated.

$$\text{Primary Mirror Width} = W_{Mirror} = 2 \times L_{M-EB} \times \left(\frac{\frac{W_{VI}}{2} - \frac{W_{Eyebox}}{2}}{L_{VID}} \right) + W_{Eyebox} \quad (5)$$

Simplifying the above equation yields:

$$W_{Mirror} = \frac{L_{M-EB}}{L_{VID}} \times (W_{VI} - W_{Eyebox}) + W_{Eyebox} \quad (6)$$

The distance $L_{M\text{-}EB}$ is shown in Figure 4.

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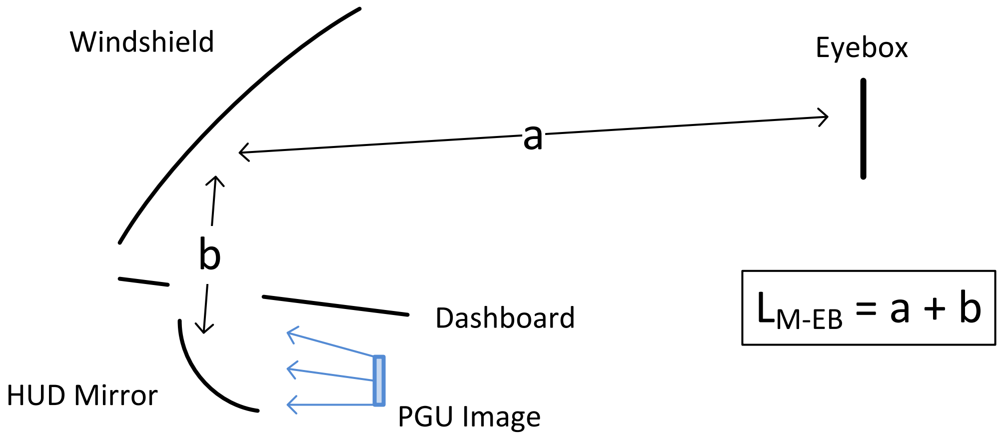

Figure 4. Distance from the eyebox to the primary mirror

4.4 Primary Mirror Height Calculations

The mirror height calculation is similar to the calculation of mirror width with the exception that the obliquity of the primary mirror needs to be taken into account. Figure 5 shows the vertical obliquity angle (theta), which is the tilt of the primary mirror (M_1) around the horizontal axis and relative to the optical axis ray. This obliquity causes the vertical dimension of the primary mirror to become elongated. This obliquity, along with the vertical FOV, creates depth in the HUD mirror optical design which will directly affect the HUD volume.

$$Primary\ \ Mirror\ \ Height = H_{Mirror} = \left[\ 2 \times L_{M-EB} \times \left(\frac{\frac{H_{VI}}{2} - \frac{H_{Eyebox}}{2}}{L_{VID}}\right) + H_{Eyebox}\right] \times \frac{1}{\cos(\theta)} \tag{7}$$

Simplifying the above equation yields

$$H_{Mirror} = \left[\frac{L_{M-EB}}{L_{VID}} \times (H_{VI} - H_{Eyebox}) + H_{Eyebox}\right] \times \frac{1}{\cos(\theta)} \tag{8}$$

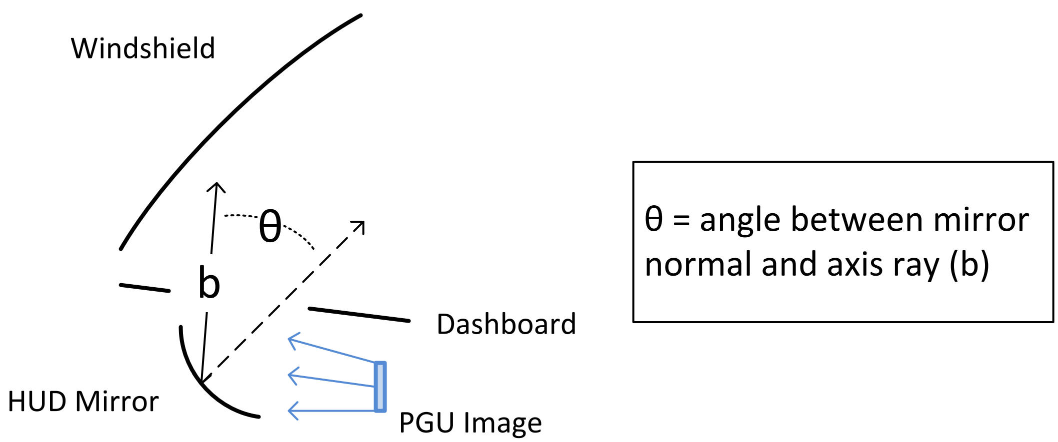

Figure 5. Obliquity angle of the primary mirror

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4.5 Comparison With Optical Design

The equations in this section can be used to estimate the size of the primary mirror in a HUD system.

HUD Specification	Value	Unit
Full Horizontal FOV	10	degrees
Full Vertical FOV	4	degrees
Virtual image distance	9993	mm
Eyebox to mirror 1	1088	mm
Eyebox full width	140	mm
Eyebox full height	60	mm
Mirror 1 obliquity angle	23	degrees
Screen to VI Magnification	25	x
Mechanical Volume Increase	30	percent
M1-M2 overlap fraction	0	percent

Figure 6. Example HUD specifications

Using the parameters listed in Figure 6, the size of the mirror can be calculated. These HUD parameters were also used to create a Zemax optical simulation of a real HUD system. The Zemax simulation is necessary when implementing a HUD, but takes a significant amount of time to design properly and is not convenient for making quick calculations and tradeoffs. Table 1 shows the mirror dimensions using both the simple equations included in this document and the calculated value from a full optical simulation.

Table 1. Estimated vs Actual Mirror Dimensions

Parameter	Estimated Value (Simple Equations)	Actual Value (Zemax)	Percent Difference
Mirror Width (W_{Mirror})	315 mm	293 mm	7.5%
Mirror Height (H_{Mirror})	141 mm	132 mm	6.8%

The calculation difference of ~7% between estimation and Zemax simulation is due to the effects of the curved windshield in the optical design model. The optical power of the windshield causes a slight reduction in mirror size from the simplified estimate. The deviation from the simplified calculation will vary slightly for every case depending on the optical power of the windshield curve. However, the estimation provides a good first-order approximation for the primary mirror size for evaluation and trade studies.

5 Estimating HUD Volume

HUD volume is much more difficult to estimate than mirror size given basic HUD system parameters. The volume depends heavily on the geometry and layout of the HUD mirror optical system which is also governed by the mechanical envelope constraints inside the dashboard. For example, a mechanical envelope with more depth may allow a HUD to be packaged into a smaller volume than a shallow mechanical depth envelope which requires folding the HUD optical path to one side. A secondary mirror, whether containing optical power or not, can be used to send the optical path back over itself and may help reduce total volume. However, even in this case, the distance between the primary mirror and screen may need to be increased in order to accommodate the fold in the optical path. This inherent inability to predict the layout of the HUD mirror optics makes it difficult to properly estimate volume.

Even with the many assumptions of the HUD volume estimates, it is still useful to try and calculate an approximate HUD volume because it can provide insight into which parameters are the primary drivers of HUD volume for a given application. A preliminary optical and mechanical system design and layout is the only way to accurately determine what FOV of HUD mirror optics can fit into a given mechanical dashboard envelope.

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The calculation for this simplified HUD volume estimation is broken down into 2 parts. The first part is the calculation of volume required by the optical path between the HUD primary mirror M_1 and the PGU diffuser screen image. This can be calculated geometrically and is based on FOV, virtual image distance, and image magnification. The second part is the estimate of mechanical volume, which includes the PGU, heat sinks, and mechanical housing of the optical components. This must be estimated based on previous design volumes. The sum of these individual parts is considered to be an estimate for total HUD volume.

5.1 Volume Between the Primary Mirror and Image Screen Calculation

The volume enclosed by connecting the corners of the primary mirror to the corners of the PGU diffuser screen image is a significant part of the HUD volume calculation. Figure 7 shows the geometry for the calculation.

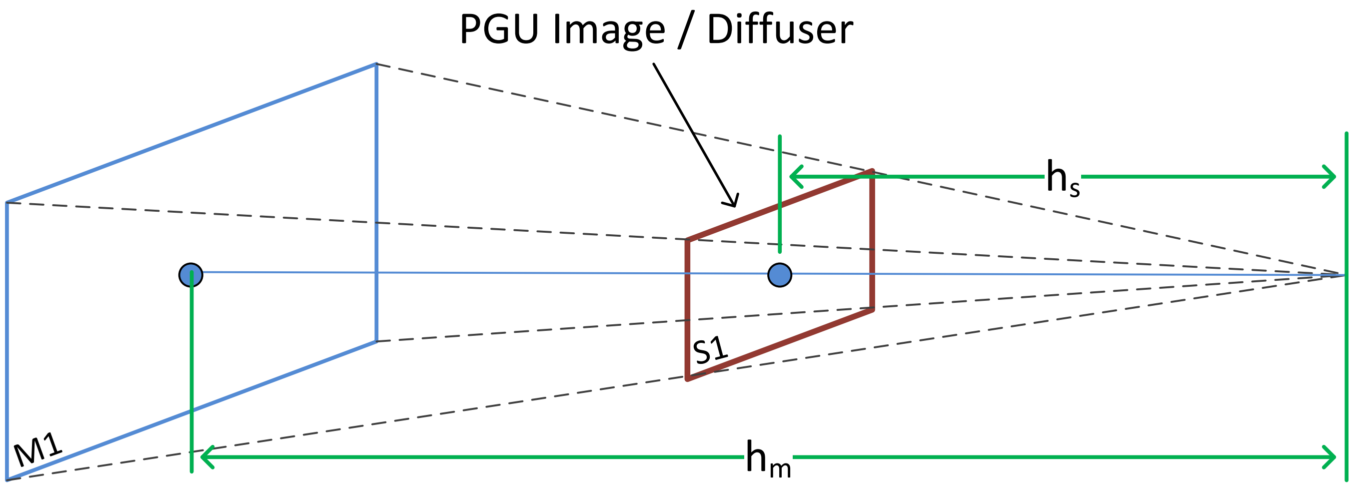

Figure 7. Geometry of the primary mirror and diffuser screen

The volume between M_1 and the diffuser screen is the difference in volume between the pyramids defined by base area or M_1 ($W_{Mirror} \times H_{Mirror}$) and height h_M and the pyramid with base area of the diffuser screen ($W_{Screen} \times H_{Screen}$) and height h_S.

$$Pyramidal\ \ Volume = \tfrac{1}{3} Length \times Width \times Height \tag{9}$$

Heights of the pyramids are found by determining the diagonal length of M_1(D_M) and the diagonal length of the diffuser screen (D_S) and where those lines intersect to form the apex of the pyramid. The diffuser screen and M_1 dimensions were determined in the previous calculation. This calculation also ignores the obliquity of M_1 for simplicity. Figure 8 and Figure 9 show the simplified geometric representation of the variables used in the calculations.

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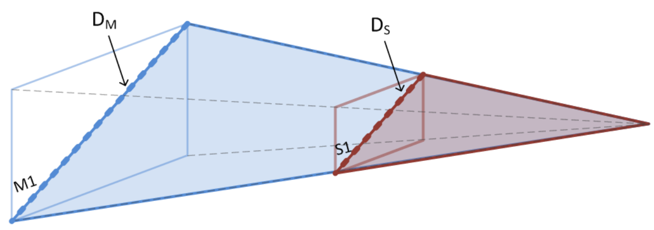

Figure 8. Diagonal area of the HUD volume pyramid

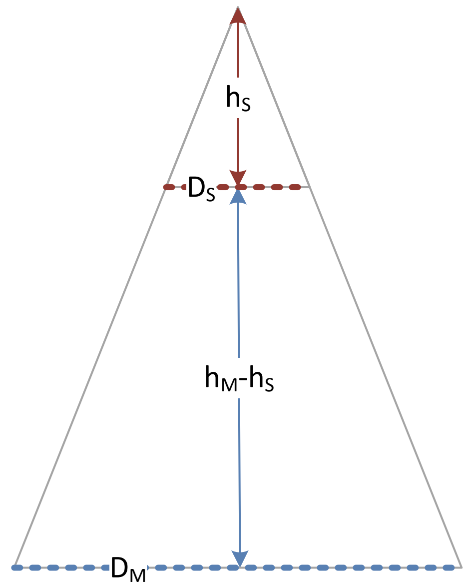

Figure 9. 2D representation of HUD volume pyramid diagonal

$$D_S = \sqrt{W_{Screen}^{\ 2} + H_{Screen}^{\ 2}} \tag{10}$$

$$D_M = \sqrt{W_{Mirror}^{\ 2} + H_{Mirror}^{\ 2}} \tag{11}$$

$$h_S = \frac{D_S \times (L_{VID} - D_M)}{Magnification \times (D_M - D_S)} \tag{12}$$

$$h_M = h_S + \frac{(L_{VID} - D_M)}{Magnification} \tag{13}$$

Using the equations above, we can use h_M and h_S for the heights of two pyramids to find the volume enclosed between the mirror and diffuser screen.

$$Volume = \frac{1}{3}(W_{Mirror} \times H_{Mirror} \times h_M) - \frac{1}{3}(W_{Screen} \times H_{Screen} \times h_S) \tag{14}$$

5.2 Volume of the Mechanical Structure and PGU Estimations

The second part of the volume calculation is the estimation of the volume taken up by the PGU and mechanical structure surrounding the HUD mirror. Figure 10 and Figure 11 show an example of the volume used by the HUD mechanics and PGU.

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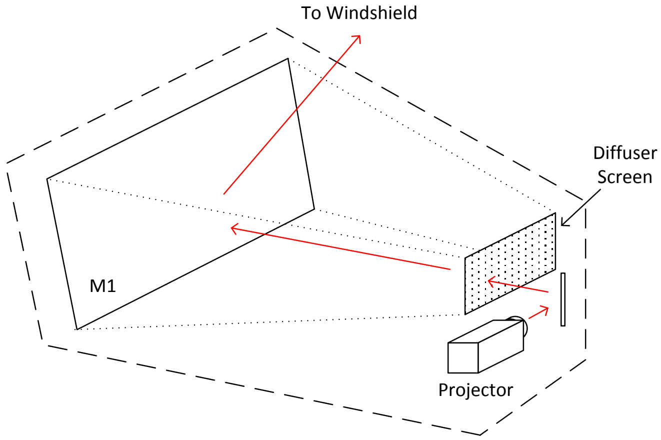

Figure 10. Mechanical volume estimate surrounding HUD optics

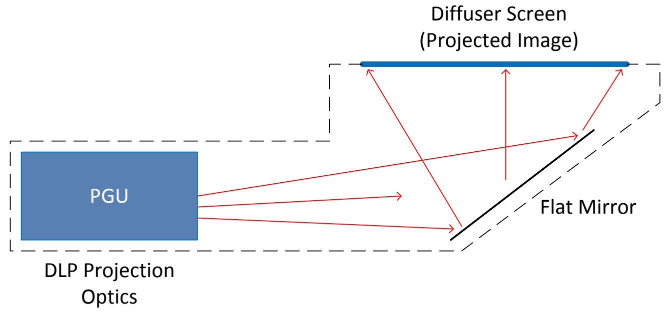

Figure 11. Example PGU layout volume measurements

Only an estimate of volume outside of the optical path between M_1 and the diffuser screen can be computed. A scaling factor can be used, which describes percentage of additional space the total HUD volume enclose compared to the volume found with Equation 14. A good starting value for this scaling factor is 30%.

5.3 Limitations of HUD Volume

It is clear based on the method of calculation that minimizing the distance between the primary mirror and the diffuser screen will be most effective at minimizing volume. However, there are limitations as to how close M_1 can be to the diffuser screen. One significant limitation is the optical beam path leaving M_1 upward to the windshield. This beam must not be vignetted by the diffuser screen, a secondary fold mirror, or any other mechanical structure. This forces a minimum spacing between M_1 and the diffuser screen/PGU. Reducing the distance between M_1 and the diffuser screen also means reducing the focal length of M_1. This causes the diffuser screen/PGU image to be smaller and can cause more optical distortions and ray aberrations which affect the image quality of the HUD. Diffuser screen images can be made smaller, up to certain limits, based on the performance and properties of the diffuser screen and the minimum pixel size at the screen. A minimum image pixel size at the screen is required to eliminate moiré or other screen artifacts caused when the projected image pixel size and diffuser screen features are similar in size.

6 Example Volume Calculations

The equations in this document can be used to estimate HUD volume for different cases and trends. They are incorporated into the AR HUD Volume Estimation Calculator for quick application and evaluation of many parameters. In the examples in Table 2, the mechanical volume increase scale factor is 30%, the mirror obliquity factor is set to 30°, and the eyebox to mirror distance is 1 m.

Table 2. Example Volume Calculations

FOV (°)	VID (m)	Eyebox (mm)	Magnification	Diffuser Screen Width (mm)	Volume (L)
8 × 3	2.4	120 × 50	5	67.1	3.4
10 × 4	10	140 × 60	25	70	8.6
12 × 5	15	140 × 120	30	84	15.6

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7 Summary

The process of designing an AR HUD can be long and requires optical, mechanical, and electronic expertise. However, final volume can be estimated to a fair degree of accuracy without the need for a complex opto-mechanical design. The method described in this document can be used to calculate a first order estimation of overall HUD volume and allows system designers to effectively evaluate the tradeoffs present in a HUD system. Smaller display designs based on the DLP3030-Q1 chipset may only require about 9 L of space to fit, while HUDs with larger displays up to 14° using the DLP5530-Q1 chipset may require 15-20 L or space. HUD volume should be a consideration early on in the overall automobile design process.

For more information on AR HUD designs and DLP technology, please see the following documents:

- AR HUD Volume Estimation Calculator
- DLP® Technology: Next generation augmented reality head-up display
- Electronics and LED Driver Reference Design for Augmented Reality Head-Up Displays
- AR HUD Lumen Budget Estimation Budget Calculator

8 References

- DLP3030-Q1 Product Folder
- DLP5530-Q1 Product Folder
- AR HUD Volume Estimation Calculator

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