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ABSTRACT

The Alliance of Automotive Manufacturers (Alliance) has produced a document in which Principle 1.4 gives criteria and methods for calculating downvision angles to navigation and telematics displays in vehicles. This paper describes the details of the criteria and methods for determining compliance. Visual displays placed high in the vehicle instrument panel help drivers to use their peripheral vision to monitor the roadway for major developments, even during brief glances to the display. The Alliance has developed two criteria to define the maximum allowable downward viewing angle for displayed information in North American vehicles. One criterion is for use in two-dimensional Computer Aided Design (CAD) analyses, and one is for use in three-dimensional CAD analyses. Alliance Principle 1.4 is consistent with known driver performance research data, and known facts about the peripheral sensitivity of the human visual system.

INTRODUCTION

Alliance Principle 1.4 reads:

1.4 Visual displays that carry information relevant to the driving task and visually-intensive information should be positioned as close as practicable [1] to the driver’s forward line of sight.

For a driver to be in full control of the vehicle and aware of the dynamic roadway there is a broad consensus that, apart from brief glances at mirrors or instrumentation, the driver's gaze should be directed towards the roadway. Visual displays positioned close to the normal line of sight reduce the total eyes-off-the-road time relative to those that are positioned further away. Such positioning also maximizes the possibility for a driver to use peripheral vision to monitor the roadway for major developments while principally looking at the display.

A manufacturer may use either Criterion 1.4A or Criterion 1.4B below to define the allowable downward viewing angle to displayed information. One is for use in two-dimensional Computer-Aided Design (CAD) analyses, and one is for use in three-dimensional CAD analyses. Both of these criteria have been derived from research that underlies a JAMA guideline on downward viewing angle. As a result, these criteria are based on a reference point called the Japanese eye point. In order to apply these practices in North America in a way that is consistent with Japanese criteria, it is necessary to establish a corresponding point in terms of North American practice. In this Principle, therefore, the term ‘eye point’ is the SAE equivalent of the JIS (Japanese Industrial Standard) eye point [2], which is the SAE J941 [3] 2D ellipse side view intersection of XX and ZZ locator (datum) lines. This corresponding point is located 8.4 mm up and 22.9 mm rearward of the mid-eye centroid of the SAE ellipse [3].

CRITERION 1.4A (2D CAD ANALYSIS)

If head-down, the display shall be mounted in a position where the 2D downward viewing angle is less than or equal to 30 degrees at the geometric center of display. Since the eye point height from the ground differs greatly between passenger cars and large trucks, the relationship between eye point height and the perceptible distance was calculated with a compensation equation given below in Eq. 1 in relation to the eye point height from the ground.

When the height of the eye point above the ground is 1700 mm or more, the display shall be mounted in the position at which the downward viewing angle shall be less than the value obtained from Eq. 1 [4]:

\[
\text{Angle (degrees)} = 0.01303 \times (\text{eye point height from the ground} (\text{mm})) + 15.07 \tag{1}
\]

Although no lateral viewing angle provision is specified, current research has validated this Principle only for display locations up to 40 degrees laterally from the driver. The intent of this Principle is to apply to visually intensive displays located in the instrument panel center stack.
CRITERION 1.4A VERIFICATION METHOD

This method represents an angular measurement done in two dimensions at the centerline of the display. It duplicates what is in the JAMA Guidelines [5].

This procedure is to be applied within a computer-aided design or modeling tool (or some equivalent measurement method). It is also intended to be applied when the seat is in its design nominal position, and the display is located at its design-intent position. This recognizes that some variations around these design nominal positions may occur at the time of vehicle build or assembly, but need not be individually measured.

If head-down, the display shall be mounted in a position where the downward viewing angle is less than 30 degrees. The downward viewing angle should be set between two lines that project on the vehicle’s degrees. The downward viewing angle is less than 30 degrees. The downward viewing angle is given by the dimensions of the CAD model in [9], their Fig. 3, which they used to express the main findings of their study in 3D terms. The maximum 3D downangle is likewise set to be dependent upon the height of the eye point above ground, again as per [9], their Eq. 5. Ground is here defined as in terms of curb weight as per SAE J1100 [8], Section 3.2.1 [11], and will be referred to as SAE curb ground or curb ground in the rest of this paper.

Fig. 2 shows an Eye Box that illustrates the symbols and variables used in describing the 3D downangle procedure.

CRITERION 1.4B (3D CAD ANALYSIS)

If information subject to this Principle is displayed at a head-down location, the displayed information must be located at or above the criterion downward viewing angle [6] at the geometric center of the active display area as determined by the following procedure [7]. Note that the “active display area” excludes unused display surface and hard switches. Fig. 1 [8, adapted from their Fig. 1] shows the three-dimensional reference system that will be used to describe the method.

The maximum allowable 3D downward viewing angle (3D downangle) for a particular vehicle is set in a manner consistent with the JAMA data [9], [10] that formed the basis for the 2D downward viewing Criterion 1.4A. In particular, the maximum allowable 3D downward viewing angle is given by the dimensions of the CAD model in [9], their Fig. 3, which they used to encompass the eye and the display. The drawing defines an eye box formed by eye point E (upper left corner of eye box), and target point T on the display (lower right corner of eye box). The X, Y, Z axes are vehicle coordinates as per Fig. 1. The view is from the right side of the vehicle towards the driver. The near plane E′T′T″ is the right face of the eye box, typically at or near the centerline of a vehicle.

Key: \( X, Y, Z \) - vehicle coordinates in front-rear (X), side-side (Y), and up-down (Z) directions; \( E \) - J.I.S. Eye Point; \( E' \) - projected E Point; \( T \) - Target point on display screen; \( T', T'' \) - projections of T point; \( b \) - downward distance (\( \Delta Z \)) from eye to target; \( c \) - forward distance (\( \Delta X \)) from eye to target; \( d \) - cross-car distance (\( \Delta Y \)) from eye to target; \( a' \) - length of 3D ray from eye point E to target point T - \( \sqrt{a'^2 + c'^2} \); \( a \) - length of eye-to-target ray \( a' \) in projected (side) view - the distance \( E'T \) from eye to target when both points are projected onto the same side plane - \( \sqrt{b^2 + c^2} \); \( \theta_{3D} \) - 3D downward viewing angle \( E'T'T \) - \( \tan(b/c) \); \( \theta_{2D} \) - 2D downward viewing angle \( E'T'T \) - \( \tan(b/a) \).
Maximum Allowable 3D Downward Viewing Angle:

The method to derive the appropriate maximum allowable 3D downward viewing angle for a specific vehicle is described below.

a) Measure the height $Z_{\text{ground}}$ of the J.I.S. eye point from the SAE curb ground [11] for the vehicle. In North America, this would be the distance from the mid-eye centroid of the SAE eyellipse [3], [12] to the SAE curb ground for that vehicle, plus 8.4 mm to convert to JIS eye coordinates.

b) Substitute the greater of $Z_{\text{ground}}$ or 1146 into the right side of Eq. 1, and calculate the angle. The calculated angle is the maximum allowable 2D downward viewing angle for that particular eye height, here termed $\theta_{2D\text{max}}$. It is measured from the JIS eye point to the display point in side view. That is, the JIS eye point and target point are projected to the same side plane, and then the angle between the two points is the maximum 2D downangle (see $\theta_{2D}$ angle $E'T'T$ in Fig. 2). Unlike Principle 1.4A, the maximum 2D downangle limit is variable for vehicles with eye-to-ground heights less than 1700 mm as well as greater than 1700 mm, following Eq. 1 and results from [9], [10]. $\theta_{2D\text{max}}$ is used here solely as an intermediate step in calculating the maximum allowable 3D downward viewing angle as per step (c). (Note: $\theta_{2D\text{max}}$ is a different angle than the criterion 2D angle described in Principle 1.4A and is not intended to be used as a substitute for the 2D angle method in section 1.4A.)

c) Convert this 2D angle solution ($\theta_{2D\text{max}}$) to a 3D angle ($\theta_{3D\text{max}}$). The 2D angle is the downangle in terms of the side view, but the 3D angle is the true downangle to the display from the driver-centered point of view, measured from the driver’s seated position. That is, the 3D downangle is measured in the rotated vertical plane in which lie both the JIS eye point and the display point. (It can loosely be thought of as associated with the downangle formed as if the driver rotated his head [13] and then looks down, to direct the center of gaze to the display point.) $\theta_{3D\text{max}}$ is the maximum allowable 3D downward viewing angle for a given vehicle with a certain eye height above ground, as given by Eq. 2.

$$\theta_{3D\text{max}} = \arctan[\tan(\theta_{2D\text{max}} - \pi/180)/\sqrt{(1 + d_{00}^2/c_{00}^2)]}$$  \hspace{1cm} (2)

Note that $c_{00}$ and $d_{00}$ in Eq. 2 are the specific vehicle dimensions from the JAMA CAD model [9] summarizing the empirical data, and not the values for the new test vehicle under investigation. The value of $c_{00}$ is the forward distance from the eye point to the vertical plane (Y-Z plane, see Fig. 1) containing the display point, and $d_{00}$ is the cross-car distance between the eye-point and the vertical plane (X-Z plane, see Fig. 1) at the centerline of the vehicle, for the JAMA CAD model [9], [14]. Yoshitsugu [15] gives these values as $c_{00} = 550$ mm, $d_{00} = 370$ mm. Substituting, Eqs. 1 and 2 may be combined and simplified into Eq. 3. This method ensures that the more general equations for the 3D downangle derived here always contain the JAMA model [9] and empirical data as a special case.

$$\theta_{3D\text{max}} = 57.2958 \times \arctan[0.829722 \tan(0.263021 + 0.000227416 \max(1146,Z_{\text{ground}}))]$$  \hspace{1cm} (3)

Fig. 3 shows that the maximum allowable 3D angle goes from 25.6 degrees at an eye height above ground of 1146 mm to 35.93 degrees at an eye height of 2000 mm.

In short, this method guarantees that the calculations for a new vehicle 3D maximum downangle encompass the empirically based CAD model and equations as given in [9]. That is, the model [9] has now been generalized to allow for a true 3D downangle, which more closely approximates the actual downangle of the driver’s visual system when observing the display.

Examples are given in the Appendix.

Justification:

A driver will be better able to monitor the roadway and the driving environment if the display location is kept as close as practicable to the driver’s forward view. A display that is located too low in the vehicle may divert the driver’s attention from the roadway and may cause a dangerous situation. Several studies on driver inattention or distraction have shown that rear-end type crashes are a predominant scenario [16], [17], [18].

This Principle is based on the JAMA Guideline [5] concerning the monitor location of image display devices, and test results on which these Guidelines are
based [9], [10]. These provisions were adopted when the JAMA Guidelines were revised in February 2000.

The JAMA study [9], [10] determined the lower limit of a display’s downward viewing angle at which drivers focused on the display are still able to perceive they are closing on a preceding vehicle within the distance needed to avoid a rear-end collision. It should be noted that, to date, this study appears to be the only one published which has addressed downward viewing angle in terms of the driver’s ability to perceive a lead vehicle at the time that a glance to an in-vehicle display is occurring. As such, it has formed the basis for criteria 1.4A and 1.4B above. However, it would be desirable to have a more substantial body of research on which to base these criteria and it is an area that deserves further research in the future so that these criteria and verification procedures can be refined. In the future, as additional research is conducted and becomes available, it can be applied to improve and solidify the criteria under Principle 1.4.

The method used in the JAMA study [9], [10] to define an allowable downward viewing angle is pertinent to the current criteria. This method included:

- **Visual target:** The visual target for the driver of the test vehicle was a preceding vehicle that was stopped on road with its brake lights illuminated.
- **Visual task:** Test subjects were instructed to watch for a preceding vehicle by means of peripheral vision while looking intently at single-digit numbers (7 mm in height).
- **Evaluation index:** The distance at which test subjects became aware of presence of the preceding vehicle by means of peripheral vision measured and defined as perceptible distance was the evaluation index for this task.

**Calculation of Lower Limit of Display:**

Based on the experimental results [9], [10] the relationship between (1) the distance at which drivers can perceive they are closing on a preceding vehicle while gazing at the monitor and (2) the downward viewing angle of the monitor, can be approximated with Eq. 4 [9] for a passenger car (eye point height from the ground of 1146 mm).

$$y = -1.151x + 85.250 \text{ (average value)} \quad (4)$$

A rear-end collision may be avoided if the following vehicle begins to brake by the time it reaches a point where the preceding vehicle started to brake. Consequently, the required headway must include braking response time of the driver of the following vehicle.

A conservative estimate of approximately 2 second headway may be considered desirable, as it includes delayed reactions and variation among drivers when braking suddenly to avoid an unexpected vehicle ahead in city driving [19]. From this headway time, at 60 km/h drivers should be able to detect a preceding vehicle at a distance of 33 meters.

This relationship is shown in Fig. 4.

![Fig. 4. Relationship between downward viewing angle of display and perceptible distance (from [9]).](image)

In order to account for individual differences in perception, judgment and vision, it was decided to subtract the average standard deviation (S.D.) of the perceptible distance from the average value. From the data in Fig. 4, the relationship between the average S.D. of the distance for perceiving a preceding vehicle and the downward viewing angle of the monitor can be approximated with Eq. 5:

$$y = -1.060x + 69.370 \text{ (average -S.D.)} \quad (5)$$

The difference in the monitor’s downward viewing angle in terms of the eye point and the normal ellipse is approximately 5 degrees, which corresponds to a difference of approximately 5 meters in the distance for perceiving a preceding vehicle (see Fig. 4). In order to account for difference in eye point positions, a margin of 5 meters should be provided for the perceptible distance.

From Fig. 4, at a perceptible distance of 33 meters in city driving, the intersection of the difference between eye point and ellipse data occurs at approximately a 30° downward viewing angle. Taking the above considerations into account, the lower limit of the downward viewing angle of the screen in a passenger car was found to be approximately 30°. This observation formed the basis for Criterion 1.4A.

The JAMA study [8], [9] also examined perceptible distance to a lead vehicle at various eye height locations (1146 mm, 1393 mm, 1737 mm, and 2388 mm). The results revealed that as drivers’ eye height above ground increases, the further they could see down the road.

Essentially, the line of sight to the lead vehicle at elevated eye heights declines slightly from horizontal. The angular distance between a lead vehicle and the
Comparison of 2D and 3D Methods

Criterion 1.4B accounts for the actual downward viewing angle of the driver’s vision system when viewing the display. Drivers typically move their head and/or their eyes to a display to bring the fovea or area of highest acuity vision onto the display. The ability of the driver to detect and respond to vehicles or objects on the road ahead when glancing downward is determined by the limits of the human peripheral visual system, more so by the up-down visual dimension rather than the left-right one, as shown in the [9], [10] data, and is well known from human visual periphery studies [20]. These limits are more closely associated with the actual downward angle in the vertical dimension of the driver’s eyes, not the 2D side angle in vehicle coordinates. Therefore, the 3D angle as shown is a better approximation to the driver’s actual downward visual angle than the 2D angle measured in the side view, from a human vision standpoint. On this basis, the 2D downangle method in 1.4A is overly strict for cross-car distances greater than the intersection point of the two curves and overly lenient for cross-car distances smaller than that intersection point (see Appendix Fig. A1). The 2D downangle method leads to a constant horizontal constraint line on the instrument panel (see Appendix Fig. A1). At greater cross-car distances, this fixed distance down leads to smaller and smaller true visual angles the further the displacement is away from the driver, just due to basic geometry. Likewise, the 2D method may be overly lenient if the cross-car location of the display were to be moved closer and closer to the driver (for example, at or near the instrument cluster). Nonetheless, the 2D method is simple to understand and implement, can be based on grid coordinates without the need for a ground plane definition, and it encourages higher and more optimal display placement at a typical display location in the center stack.

CRITERION 1.4B VERIFICATION (FOR USE WITH 3D CRITERION ANGLES):

This verification procedure is appropriate for use with Criterion 1.4B (and represents an angular measurement done in three dimensions from eye point height at the driver’s seated position). It is also appropriate when the height and width of a vehicle might differ from those for which the simpler 2D criterion and measurement were developed.

This procedure is to be applied within a computer-aided design or modeling tool (or some equivalent measurement method). It is also intended to be applied when the seat is in its design nominal position, and the display is located at its design-intent position. This recognizes that some variations around these design nominal positions may occur at the time of vehicle build or assembly, but need not be individually measured.

Three alternate methods are given for Section 1.4B, all of which produce an equivalent answer. In all three methods for 1.4B, it is perhaps easiest to first translate and then rotate the world coordinate system (WCS) to align with the SAE curb ground plane. The original grid coordinate system (as in Fig. 1) must not be used, or it violates the assumptions of Criterion 1.4B.

Method 1 – CAD Measurement

1. Ensure that both the driver’s seat and the display to be analyzed are placed at their respective nominal design positions in the three-dimensional CAD representation (or equivalent).
3. Determine the location of the centroid of the combined eyellipse (mid-eye centroid), and then find the point corresponding to the Japanese eye point, 8.4 mm up and 22.9 mm back for the SAE eyellipse.
4. Determine the location of the display point, defined as in the first paragraph of Section 1.4B.
5. Determine the 3D downward viewing angle. This can be done by going through steps a, b, and c, below or by using some simple CAD methods noted after step c.

a. Construct a line representing the driver’s line-of-sight to the display point. This can be done by drawing a line between the eye point (located in step 3, above) and the display point (located in step 4, above). This represents the line-of-sight to the displayed information. (See line ET in Fig. 2).

b. Construct a line in the horizontal plane of the driver’s eye point, to a point in that plane directly above the display point (line ET’ in Fig. 2). The angle that lies between these two lines (the line of sight to a point in the horizontal viewing plane directly above the display point and the line of sight to the display point) represents the actual downward viewing angle to the display point.
c. Measure (or calculate) the size of the 3D downward viewing angle using the formula \( \theta_{3D} = \arcsin \left( \frac{b}{a'} \right) \) (see Fig. 2), where:

\[ a' = \text{Distance from eye point to display point along the line of sight ET to the display.} \]

\[ b = \text{Vertical distance from the eye point down to the horizontal plane encompassing the display point (line } T'T \text{ in Fig. 2).} \]

If this angle is equal to or less than the maximum allowable downward viewing angle computed for Criteria 1.4B, then the display location meets the criterion.

**Method 2 – Swept Line Method**

Another way to implement this verification method in a Computer Aided Design (CAD) system is to create a swept line. Construct a single line that has a fixed angle down from the horizontal plane containing the eye point – that is, a fixed angle down from the driver's forward line of sight to the roadway. The down angle to the forward line of sight should be set at a value of \( \theta_{3D_{\text{max}}} \) – the maximum allowable 3D downward viewing angle (as determined from Criteria 1.4B). Once anchored and positioned this way, the line can be swept laterally, such that it makes a constant downangle with the horizontal plane containing the eye point. This swept line will trace an intersection path on the dashboard representing the lower limit for the display point. This trace is the 3D constraint line. If the displayed information lies above the intersection of the display and this constraint line, it is considered to meet the 1.4B downward viewing angle requirement.

The swept line also creates a cone [21]. The cone that is generated by the swept line is illustrated in Figs. 5-7. Fig. 5 is a perspective view, Fig. 6 is a side view, and Fig. 7 is a rear view. The apex of the cone is at the eye point \( E \). If the criterion display point were inside the boundary of the cone shown, the component placement would not meet criterion 1.4B. Because it is outside the boundary of the cone (see Fig. 7), it meets criterion 1.4B [22]. The intersection of the cone with the vertical YZ plane containing the display point traces a hyperbola, which is the line shown in Appendix Fig. A1, labeled “1.4B 3D constraint line.”
Method 3 – Two-Point Math-Based Method

A final way to implement method 1.4B is to ask a CAD operator to determine the X, Y, Z values of two points: the mid-eye ellipse centroid, and the display point. (Note: the X and Z values need to be determined with respect to the SAE curb ground plane 11, not the grid coordinate system of the vehicle as in Fig. 1.) Then the formulas given below can be easily placed for example in an Excel spreadsheet to calculate the maximum allowable 3D angle, and the actual 3D angle.

Let $X_{\text{display}}$, $Y_{\text{display}}$, $Z_{\text{display}}$ be the coordinates of the display. Let $X_{\text{eyeSAE}}$, $Y_{\text{eyeSAE}}$, and $Z_{\text{eyeSAE}}$ be the SAE eye coordinates. Then calculate the JIS eye point as per Eqs. 6:

$$X_{\text{eyeJIS}} = X_{\text{eyeSAE}} + 22.9 \text{ (rearward)}$$  
$$Y_{\text{eyeJIS}} = Y_{\text{eyeSAE}}$$  
$$Z_{\text{eyeJIS}} = Z_{\text{eyeSAE}} + 8.4 \text{ (upward)}$$  

(6)

Then calculate:

Forward distance from eye point to display point ($\Delta X$ or $c$) = $X_{\text{eyeJIS}} - X_{\text{display}}$

Cross-car distance from eye point to display point ($\Delta Y$ or $d$) = $Y_{\text{eyeJIS}} - Y_{\text{display}}$

Actual height distance from eye point to display point ($\Delta Z$ or $b$) = $Z_{\text{eyeJIS}} - Z_{\text{display}}$

Length of eye-to-target ray in true (i.e. 3D) view ($a'$) = $\sqrt{b^2 + c^2 + d^2}$  

(7)

Finally calculate:

Maximum 2D downangle for this eye height = $\theta_{2D\text{max}} = 0.01303 \cdot Z_{\text{eyeJIS}} + 15.07$

Maximum 3D downangle for eye height = 57.29°ATAN($\theta_{2D\text{max}}\cdot 0.017$/SQRT($1 + d_{00}^2 / c_{00}^2$))

Actual 3D downangle = DEGREES(ASIN($b/a'$))  

(8)

Note that $c_{00}$ must be fixed at 550 mm, and $d_{00}$ at 370 mm, based on the JAMA CAD model of the experimental results (see section “Maximum Allowable 3D Downward Viewing Angle”).

Examples:

Good: Visual display positioned high on the instrument panel towards the driver’s side of the central console, but not being obstructed by the steering wheel or obstructing the forward vision.

Bad: Display positioned too low in the console area towards the front passenger’s side or within a glove compartment.

DISCUSSION AND CONCLUSION

Two methods of downangle calculation are shown which both are consistent with known data on the ability of drivers to detect and respond to a vehicle brake light in a vehicle in front of them. At this point in time, either method of downvision calculation can be a useful tool to assess vehicles for compliance with Principle 1.4

Additional studies are recommended to further test and validate the Alliance Principle 1.4 criteria and model. These methods also be further refined and explored to determine sensitivity to both vertical and horizontal vision. Further mathematical modeling work can potentially unify the 2D and 3D criteria into a single downangle metric. The objective would be to merge the motion and luminance contrast sensitivity contour plots of the human visual system as a function of retinal eccentricity, into a common mathematical model with the geometry of the driver, roadway scene, display, and vehicle interior.

In conclusion, downvision metrics are presented with verification procedures to ensure that visual displays that carry information relevant to the driving task and visually-intensive information shall be positioned such that a driver’s peripheral vision can still monitor the roadway for visual changes when the driver briefly glances at a display.
ACKNOWLEDGMENTS

The authors would like to acknowledge help and support from the Alliance members who contributed time and effort to this endeavor, but especially: Linda Angell, General Motors Corporation; Don Mission, Daimler-Chrysler Corporation; and Gary Rupp, Ford Motor Corporation. This paper is dedicated to the memory of our esteemed colleague and dear friend W. Weston Meyer, 12/1/21 - 11/24/04.

REFERENCES AND NOTES

[1] Practicability is introduced to allow a reasonable trade-off between closeness to the driver's normal line of sight and other issues of allocation of devices to a limited instrument panel space.
[2] JIS Eye Point is defined by JIS D0021 and JIS D1702.
[4] The coefficient of the eye height from ground is set at 0.01303 to be consistent with the JAMA published guidelines [5], although 0.013 is used in Eq. 5 in [9]. Yoshitsugu et al. (2000). This difference does not materially affect the calculations.
[6] Although no lateral viewing angle provision is specified here, [9] validated this principle only for display locations up to 40 degrees laterally from the driver.
[7] Alternatively, the display may be mounted in a position where the downward viewing angle is less than or equal to the criterion viewing angle at the geometric center of display.
[11] In Section 1.4B, coordinate dimensions are specified as per SAE J1100 Revised JUL2002 [8]: "Unless otherwise specified, all dimensions are measured normal to the three-dimensional reference system (see SAE J182), except ground-related dimensions, which are defined normal to ground. All dimensions are taken with the vehicle at curb weight unless otherwise specified." The term curb weight is defined in SAE J1100 Revised JUL2002 section 3.2.1: "CURB LOAD, CURB WEIGHT—The weight of the base vehicle (standard equipment only), with all fluids filled to maximum (fuel, oil, transmission, coolant, etc.)." SAE curb weight shall define the ground plane for Section 1.4B of this document. Numerous other definitions of ground planes have been used both internally by vehicle OEMs and by U.S. government agencies for various purposes. However, other definitions are subject to interpretation, such as the specification of optional vehicle content. SAE curb weight is currently the only ground plane on which vehicle values are routinely publicly reported by vehicle companies selling in North America. Finally, the tire size tends to be smallest in the base vehicle, leading to a lower eye height and stricter section 1.4B criterion compared to larger tire sizes (see main body section "Maximum Allowable 3D Viewing Angle"). It is to be noted that the zero-grid Z plane (see main body Fig. 1) must not be used as the ground plane for Section 1.4B, because it is an arbitrary grid not directly related to true ground.
[13] Technically the current method is equivalent to rotating the eye, not the head.
[14] The centerline of the vehicle and the centerline of the display coincide in the JAMA model [9], [10].

[21] Note: This cone should not be confused with the cone of vision or the effective or inductive field of vision as referred to by [9], their Fig. 3.

[22] Although no lateral viewing angle provision is specified, current research has validated this principle only for display locations up to 40 degrees laterally from the driver.

[23] The $\theta_{D\text{max}0}$ value can be easily calculated in the JAMA CAD model [9] because the center point of the display was at the center line of the vehicle – that is, the display was centered on the center stack in the middle of the vehicle, midway in cross-vehicle distance between the driver and the passenger.

[24] Note that the 2D angle shown here is calculated in ground coordinates, but it is often necessary in practice to calculate it in grid or vehicle coordinates (main body Fig. 1) early in vehicle design, when no ground plane may be defined.

[25] The general constraint solution for a curved or sloping instrument panel is more complicated than for the planar assumption, but can be established via a direct CAD model measurement if desired.

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ADDITIONAL SOURCES


DEFINITIONS, ACRONYMS, ABBREVIATIONS

2D: Two-dimensional space

3D: Three-dimensional space

Alliance: Alliance of Automobile Manufacturers

CAD: Computer-Aided Design

JAMA: Japanese Automobile Manufacturers Association

JIS: Japanese Industrial Standard

SAE: Society of Automotive Engineers

APPENDIX

EXAMPLE 1: JAMA CAD MODEL CAR

For the eye height $Z_{\text{ground}}$ of 1146 mm used in the JAMA CAD model [9], the $\theta_{D\text{max}0}$ value via Eq. 2 is exactly 30 degrees (the identical 30-degree 2D downangle limit value as per Criterion 1.4A) [23]. The maximum permissible 3D downangle $\theta_{D\text{max}0}$ for [9], their Fig. 3, for the eye height of 1146 mm is then 25.6 degrees via Eq. 2 or Eq. 3 (see point labeled “Example 1” in Fig. 3).

Table A1 gives parameters of the driver-car model that match to the forward event braking data [9]. The 3D downangle limit is 25.6 degrees for the particular car used in study [9] with the parameters given, when the display is at the maximum 2D downangle of 30 degrees.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Symbol</th>
<th>JIS Eye</th>
<th>Units</th>
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<td>J.I.S. eye point height from SAE curb ground</td>
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<td>mm</td>
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<td>Maximum 3D downward viewing angle for this eye height</td>
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<td>Cross-car distance from eye point to display point ($\Delta Y$)</td>
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<td>mm</td>
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<tr>
<td>Height distance from eye point to display point ($\Delta Z$)</td>
<td>$b_0$</td>
<td>317.54</td>
<td>mm</td>
</tr>
<tr>
<td>Length of eye-to-target ray in projected (i.e. side view)</td>
<td>$a_0$</td>
<td>635.09</td>
<td>mm</td>
</tr>
<tr>
<td>Length of eye-to-target ray in true (i.e. 3D view)</td>
<td>$a_0'$</td>
<td>735.01</td>
<td>mm</td>
</tr>
<tr>
<td>2D downward viewing angle (curb ground)</td>
<td>$\theta_{200}$</td>
<td>30.00</td>
<td>deg</td>
</tr>
<tr>
<td>3D downward viewing angle (curb ground)</td>
<td>$\theta_{b00}$</td>
<td>25.60</td>
<td>deg</td>
</tr>
</tbody>
</table>

Table A1. Parameters for the CAD model that matches the empirical driver performance braking data to forward events[9]. The maximum 2D downward viewing angle is 30 degrees, which the display location just meets. The corresponding maximum 3D downward viewing angle is 25.6 degrees (for SAE curb ground), which the display location also just meets.
Fig. A1 illustrates a more general 3D solution that includes the CAD model [9] as a special case. For illustrative purposes, it is easiest to reference the driver coordinate system to an eye point located at (0, 0, 0). The 2D downward viewing angle of the display point (marked T in Fig. A1) is at the 2D maximum of 30 degrees. The horizontal 2D constraint line in Fig. A1 shows that the 2D angle stays fixed at 30 degrees (317.54 mm below the eye point in side view) as a function of cross-car distance. The curved line in Fig. A1 labeled “1.4B 3D constraint line” gives the permissible maximum permissible downward distances for the 1.4B criterion for that vehicle as a function of cross-car distance. The 3D downward viewing angle is fixed at 25.6 degrees for that curved line.

The 3D constraint line in Fig. A1 is equivalent to assuming a line is positioned with one end at the eye point, and the other at the instrument panel. The line is then swept from the centerline of the driver (that is, from \( d = 0 \) mm), to some position to the right of the centerline of the vehicle (say \( d = 800 \) mm). The intersection of the line with the vertical YZ plane in which the display point lies is the 3D constraint line in Fig. A1. The length of the line (or ray) from the eye point to the display point is given by Eq. A1.

\[
a' = \sqrt{a_0^2 + d^2} \quad (A1)
\]

The downward physical limit \( b_{\text{sweep}} \) is where the swept line intersects the vertical YZ plane in which the display point lies. This sweep is a hyperbola, given by Eq. A2.

\[
b_{\text{sweep}} = a' \sin(b_{3D_{\text{max}}} \cdot \pi/180) \quad (A2)
\]

This swept line in fact traces out a cone in 3D. Let \( C \) denote a right circular cone with apex at the eye point, central axis vertical, and central (or apex) angle equal to \((180 - 2 \cdot b_{3D_{\text{max}}})\) in degrees. (Note: the central angle of a cone is the angle across the full diameter of the cone, not just its radius.) Then every longitudinal (or rectilinear) element of \( C \)'s surface is a line of sight deflecting downward from the horizontal plane by the angle \( \theta_{3D_{\text{max}}} \). Moreover, the surface of \( C \) is the locus of all such lines of sight. It does not take a great deal of geometric intuition to see the validity of this construction. Clearly, every longitudinal element of a right circular cone's surface makes a fixed angle with the central axis, that angle being one-half the apex angle – in the case of \( C \), this half-angle is \((90 - \theta_{3D_{\text{max}}})\). If the central axis is vertical, the angle with respect to the horizontal is \( \theta_{3D_{\text{max}}} \).

This swept line or cone method is further described and illustrated in the verification “Method 2 – Swept Line Method” for Principle 1.4B, and main body Figs. 5-7. Without benefit of analysis, we know that the intersection of \( C \)'s surface with a vertical plane must be a hyperbola. (In the study of conic sections, a cone extends to infinity in both directions from the apex, so that a plane parallel to its axis will intersect the cone's surface in two disconnected branches, necessitating that the intersection be hyperbolic. In our case, we are interested only in that half of the cone that lies below the apex, and only in the lower branch of the hyperbola.) The volume inside the cone represents the locations in which the display point should not be placed.

The 2D angle constraint line (assuming SAE curb ground) is the dashed line in Fig. A1, given by the constant height \( b = a' \sin(30 \cdot \pi/180) \).

Fig. A1 shows that when the display point is closer to the driver than the intersection of the two constraint lines, the 3D constraint line is higher (i.e., stricter) than the 2D constraint line given by Section 1.4A (assuming SAE curb ground for both), whereas the opposite is true for display positions to the right of the intersection point. Hence the 3D method in Section 1.4B is neither stricter nor more permissive than the 2D method in Section 1.4A; it depends upon the cross-car distance of the display (see also main body section “Comparison of 2D and 3D Methods”).

![Fig. A1. The graph depicts a view from the rear of the vehicle towards the instrument panel. The graph describes a vertical YZ plane containing the display point T in Example 1, which is based on the car CAD model [9]. The dashed horizontal line shows the 2D design constraint line above which the display point T must be placed, for different cross-car positions d (X-axis). The solid curved line is the 3D design constraint line, above which the display point must be placed to meet criterion 1.4B. As long as the display point T is at or above either the 2D or 3D constraint line, it meets criterion 1.4. In this case, the target point T meets both 1.4A and 1.4B criteria. Point T in this CAD model [9] example is at the exact intersection of the 2D and 3D constraint lines.](image)

Obviously, other vehicles will have different sizes than in the JAMA data and model [9], [10]. Principle 1.4B generalizes the 2D Principle 1.4A to three dimensions,
with a true ground line, and ensures that common 3D downangle methods are used for vehicles of different sizes, while ensuring that the JAMA empirical model [9] is always included as a special case.

EXAMPLE 2: CRITERION 1.4B SOLUTION FOR A NEW VEHICLE DESIGN

Assume a new vehicle has eye height from SAE curb ground of \( Z_{\text{ground1}} \). Let the \( X \), \( Y \), \( Z \) distances between the eye point and the display point in the new vehicle be \( c_1 \), \( d_1 \), and \( b_1 \), respectively. That is, assume forward distance \( c_1 \), cross-car distance \( d_1 \), and height offset \( b_1 \) between the eye point and the display point. By substituting the actual eye height \( Z_{\text{ground1}} \) in Eq. 1, the maximum allowable 2D downward viewing angle \( \theta_{2Dmax1} \) for the new vehicle may be calculated. (Note that \( \theta_{2Dmax1} \) is just an intermediate 2D angle used for calculating the 3D angle, and is not the same 2D angle criterion as in section 1.4A.) The maximum 3D downangle \( \theta_{3Dmax1} \) permitted for this new vehicle design is then derived from main body Eq. 2 or Eq. 3.

To determine if the new vehicle meets the 3D downangle criterion from Section 1.4B, calculate the corresponding length of the line from the eye point to the display point in side view, given by \( a_1 = \sqrt{b_1^2 + c_1^2} \). Then the distance \( a_1' \) from the eye point to the display point along the line of sight to the display is given by \( a_1' = \sqrt{a_1^2 + d_1^2} \). The 3D downangle for this vehicle is then \( \sin(b_1/a_1') \), which can be compared with the limit \( \theta_{3Dmax1} \).

To illustrate, Table A2 shows a vehicle with its SAE ellipsoidal coordinates, as well as its JIS eye coordinates and display coordinates measured according to the SAE curb ground plane [11].

### Table A2. Eye centroid and display position for car Example 2, measured from SAE curb ground.

<table>
<thead>
<tr>
<th>Dimen. Descr.</th>
<th>Dim</th>
<th>SAE Eye Ellipse Centroid</th>
<th>JIS Eye Point</th>
<th>Display Point</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance behind the front of vehicle</td>
<td>( X )</td>
<td>3011.31</td>
<td>3034.21</td>
<td>2506</td>
<td>mm</td>
</tr>
<tr>
<td>Side distance from car centerline</td>
<td>( Y )</td>
<td>-370.00</td>
<td>-370.00</td>
<td>12</td>
<td>mm</td>
</tr>
<tr>
<td>Height above SAE curb ground</td>
<td>( Z )</td>
<td>1327.28</td>
<td>1335.68</td>
<td>969</td>
<td>mm</td>
</tr>
</tbody>
</table>

Fig. A2 shows a side view graph of the point locations in Table A2 along with a CAD model representation of the human mannequin commonly used in automotive applications. Fig. A3 shows the rear view of the same data. Neither view shows the true 3D downangle, which can only be seen in an oblique view.

Table A3 shows the 2D and 3D angle calculations for the Example 2 vehicle, based on the JIS eye point and display point in Table A2, assuming SAE ground coordinates [24]. The display point \( T \) is at a 3D downangle value of 29.36 degrees and must be moved up on the instrument panel such that a vertical height increase of at least 1.52 degrees (22.46 mm) occurs, in order to meet the 3D downangle limit of 27.64 degrees. Note that the dashboard is usually curved and tilted rather than a vertical plane, so the offset height increase required to meet the criterion should only be viewed as approximation to the actual distance that the display needs to be moved up on the dashboard itself. The final position of the display on the dashboard should be again validated against the criterion after the display is moved upwards in the CAD model.
Fig. A3. Rear view. J.I.S. eye point E, projected eye point E’ and display point T” for car example 2, projected into the YZ plane. The angle $\theta'$ formed from triangle EET” as shown is $\arctan(b/d) = 43.84$ degrees. Only the view in the oblique plane formed by ETT (see for example main body Fig. 2) will directly show the correct 3D downangle of 29.36 deg.

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Symbol</th>
<th>JIS Eye</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>J.I.S. eye point height from SAE curb ground</td>
<td>$Z_1$</td>
<td>1335.77</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum 2D downward viewing angle for this eye height</td>
<td>$\theta_{2D max 1}$</td>
<td>32.48</td>
<td>deg</td>
</tr>
<tr>
<td>Maximum 3D downward viewing angle for this eye height</td>
<td>$\theta_{3D max 1}$</td>
<td>27.84</td>
<td>deg</td>
</tr>
<tr>
<td>Forward distance from eye centroid to display point ($\Delta X$)</td>
<td>$c_1$</td>
<td>528.21</td>
<td>mm</td>
</tr>
<tr>
<td>Cross-car distance from eye point to display point ($\Delta Y$)</td>
<td>$d_1$</td>
<td>-382.00</td>
<td>mm</td>
</tr>
<tr>
<td>Height distance from eye point to display point ($\Delta Z$)</td>
<td>$b_1$</td>
<td>366.77</td>
<td>mm</td>
</tr>
<tr>
<td>Length of eye-to-target ray in projected (i.e. side) view</td>
<td>$a_1$</td>
<td>643.06</td>
<td>mm</td>
</tr>
<tr>
<td>Length of eye-to-target ray in true (i.e. 3D) view</td>
<td>$a'_1$</td>
<td>747.96</td>
<td>mm</td>
</tr>
<tr>
<td>2D downward viewing angle (curb ground)</td>
<td>$\theta_{2D 1}$</td>
<td>34.77</td>
<td>deg</td>
</tr>
<tr>
<td>3D downward viewing angle (curb ground)</td>
<td>$\theta_{3D 1}$</td>
<td>29.36</td>
<td>deg</td>
</tr>
</tbody>
</table>

Table A3. 3D downangle calculations for car in Example 2 based on J.I.S. eye point.

It would again be useful for design and vehicle architecture purposes to evaluate the downward viewing limit for the vehicle not just for one particular display location, but for an extended constraint line on the instrument panel above which the display point should be placed. This constraint line allows determination of how high the display must go for all side-to-side positions along the instrument panel [25]. By treating the cross-vehicle distance $d$ as a variable, a 3D downangle constraint line $b_{\text{sweep}}$ on the instrument panel as a function of $d$ is then given by substituting $a_1$ into Eq. A1 for $a_0$, and $\theta_{3D max 1}$ for $\theta_{3D max 1}$ in Eq. A2. The intersection of a plane and a swept line at a constant downangle from the horizontal, traces a hyperbola (see main body section "Method 2 – Swept Line Method").

Fig. A4 illustrates this constraint line method for the car parameters in Example 2. It can be easily seen that the target point T in Fig. A4 is in the restricted zone for both the 1.4A and 1.4B downangle criteria. Fig. A4 and the data in Table A3 indicate that the display must be raised at least 22 mm vertically to meet the 3D criterion of Principle 1.4B.