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Vehicle Rearview Image Field of View and Quality Measurement

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16. Abstract

The Cameron Gulbransen Kids Transportation Safety Act of 2007 required the National Highway Traffic Safety Administration (NHTSA) to "initiate a rulemaking to revise Federal Motor Vehicle Safety Standard 111 (FMVSS 111) to expand the required field of view to enable the driver of a motor vehicle to detect areas behind the motor vehicle to reduce death and injury resulting from" backover crashes. It stated that this may be accomplished "by the provision of additional mirrors, sensors, cameras, or other technology to expand the driver's field of view."

This report provides additional details regarding the analyses summarized in the December 2010 FMVSS No. 111 NPRM that provided the basis for proposed improved vehicle rear visibility requirements. A more detailed description is presented of the analysis performed to identify what area (i.e., field of view) should be visible to a driver behind a vehicle in order for that driver to have the best opportunity to avoid a backover crash. Likewise, the report contains a detailed description of the basis for determining the proposed criteria for minimum image quality that would need to be present in a rearview image in order for a driver of average vision to have the ability to discern child-sized obstacles located within the field of view.

Test procedures that were developed to assess how well a rearview image meets the proposed field of view and rearview image quality requirements are described in detail. These procedures were developed using available existing systems covering the appropriate field of view (of which all were rearview video systems). The procedures are also considered to be useable for other technologies (such as mirrors or fiber optics) that might be used to provide visual images of the area directly behind a vehicle in the future. The test procedure involves taking a photograph of the rearview image showing several objects of known locations and dimensions from the perspective of a 50th-percentile male driver. The apparent width of an object in a photograph of the display is used to calculate the subtended visual angle of test objects (which can be related to a driver's ability to see each object).

This report demonstrates the measurement procedure by applying it to six 2010-11 model year vehicles equipped with original equipment rearview video systems. One important result obtained in this testing is that a 2.4-inch diagonal sized rearview image is not large enough to provide the degree of minimum image quality proposed in the NPRM.

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EXECUTIVE SUMMARY

The Cameron Gulbransen Kids Transportation Safety Act of 2007[1] required the National Highway Traffic Safety Administration (NHTSA) to "initiate a rulemaking to revise Federal Motor Vehicle Safety Standard 111 (FMVSS 111) to expand the required field of view to enable the driver of a motor vehicle to detect areas behind the motor vehicle to reduce death and injury resulting from backing incidents, particularly incidents involving small children and disabled persons." It stated that this may be accomplished "by the provision of additional mirrors, sensors, cameras, or other technology to expand the driver's field of view."

Prior NHTSA research has shown that systems providing the driver with a 3.5-inch[2] (measured diagonally) or larger visual image of the area behind the vehicle are more effective than other types of technologies in aiding the driver to avoid a backing crash. However, for drivers to see and identify objects behind a vehicle equipped with a system providing a rearview image, the system must have an adequate field of view and the visual image must be of sufficient quality to permit the average driver to discern critical objects within the field of view.

To determine what critical field of view a driver should be able to see behind a vehicle in order to have the best chance of preventing a crash with a rear obstacle while backing, NHTSA performed Monte Carlo simulations and studied NHTSA Special Crash Investigation reports of backover crashes. The data suggest that backover crash victims tend to be located in an area 10.0 feet (3.05 meters) wide by 20.0 feet (6.10 meters) long behind a vehicle at the start of a backing maneuver. As such, NHTSA proposed an area 10.0 feet wide by 20.0 feet long immediately behind the vehicle that the driver must be able to see when the vehicle is in reverse gear.[3] Based on the criteria specified in the NPRM, a procedure was developed in which the area of interest was outlined with 7 cylindrical test objects. Each test object was a cylinder having a 12.0-inch (305 mm) diameter and 32.0-inch (813 mm) height to approximate the size of a young child. To ensure that detection of a child, if present behind the vehicle is possible, criteria for the portion of each test object that must be visible were established. For test objects located 10.0 feet (3.05 meters) or more aft of the vehicle's rear bumper, the entire height and width of each test object was required to be visible. This criterion equates to the driver being able to see the entire body of an 18-month-old. For test objects close to the test vehicle, a 5.9-inch (150 mm) wide portion of the test object was required to be visible at some point along the height of each cylinder. to ensure that, at a minimum, an area the size of a child's face would be visible and likely result in successful visual recognition of the child's presence by the driver.

The procedure for measuring image quality used in this research also used the noted cylindrical test objects to assess whether a rearview image provides sufficient detail to enable a driver to identify objects behind the vehicle within the specified field of view. Similar to the procedures developed for school bus mirror requirements in FMVSS No. 111[4], apparent angular size (as

[1] Cameron Gulbransen Kids Transportation Safety Act of 2007, (Pub. L. 110–189, 122 Stat. 639–642), § 4 (2007).
[2] Rearview images sizes examined included 2.4 inches (measured diagonally), 3.5 inches, and larger sizes. Test results showed that the reduction in crashes with an unexpected rear obstacle for the 3.5-inch image system (48 percent) was nearly twice that seen with a 2.4-inch image (26 percent) system or ultrasonic sensors (25 percent).
[3] 75 FR 76186, December 7, 2010
[4] Garrott, W. R., Rockwell, T. H., and Kiger, S. W., *Ergonomic Research on School Bus Cross View Mirror Systems*, National Highway Traffic Safety Administration, DOT 807 676, 1990.

displayed in the rearview image) was calculated for each test object of known actual size and location using (1) the distance between the rearview image as installed in the vehicle and a camera, mounted so as to represent the view observable by a 50th-percentile height male driver and (2) the test object's scaled linear dimensions as seen in a photograph of the rearview image. Details of the calculation procedure are provided in the main body of the report. The apparent angular size of specified test objects was then evaluated with respect to the asserted criteria to determine whether drivers will be able to adequately see each test object. The criteria were as follows:

1. When the apparent angular size of the three test cylinders that are located 20 feet (6.10 meters) aft of the rearmost point on the vehicle's rear bumper (Cylinders A, B, and C) are measured, the average apparent angular size of the three must not be less than 5 minutes of arc when viewed in the rearview image.
2. When viewed in the rearview image, the apparent angular size of each individual test cylinder must not be less than 3 minutes of arc.

There is no need for size criteria based on the apparent angular size requirements for any of the nearer test objects, because the three furthest test objects will always appear to be the smallest[5], thus representing the worst case for visibility among the seven equally-sized cylinders.

While in recent years rearview video systems a popular vehicle equipment option to aid drivers in performing backing maneuvers, other technologies capable of providing a rearview image are possible. These other technologies may include mirrors or fiber optic-based systems could also be used to provide the driver with an image of the area behind the vehicle. The test procedures developed in this report could also be applied to those technologies.

In order to demonstrate the measurement procedure defined herein, field of view and image quality for six model year 2010-2011 test vehicles equipped with original equipment rearview video systems were measured. All six test vehicles' rearview video systems met the field of view requirements described in the Notice of Proposed Rulemaking for FMVSS No. 111 published in December 2010.[6] The rearview video systems of five of the six test vehicles would meet both of the noted image quality criteria.

[5] For reasonably foreseeable camera locations and lens properties.
[6] 75 FR 76186, December 7, 2010

1.0 INTRODUCTION

1.1 Background

The Cameron Gulbransen Kids Transportation Safety Act of 2007[7] required the National Highway Traffic Safety Administration (NHTSA) to "initiate a rulemaking to revise Federal Motor Vehicle Safety Standard No. 111 (FMVSS 111) to expand the required field of view to enable the driver of a motor vehicle to detect areas behind the motor vehicle to reduce death and injury resulting from backing incidents, particularly incidents involving small children and disabled persons." It stated that this may be accomplished "by the provision of additional mirrors, sensors, cameras, or other technology to expand the driver's field of view."

Prior NHTSA research has shown that systems providing the driver with a 3.5-inch[8] (measured diagonally) or larger visual image of the area behind the vehicle are more effective than other types of technologies in aiding the driver to avoid a backing crash. However, for drivers to see and identify objects behind a vehicle equipped with a system providing a rearview image, the system must have an adequate field of view and the visual image must have sufficient quality to permit the average driver to discern critical objects located within the field of view.

1.2 Purpose of This Report

This report provides additional details regarding the analyses summarized in the December 2010 FMVSS No. 111 NPRM[9] that provided the basis for proposed improved vehicle rear visibility requirements. A more detailed description is presented of the analysis performed to identify what area (i.e., field of view) should be visible to a driver behind a vehicle in order for that driver to have the best opportunity to avoid a backover crash[10]. The report contains a detailed description of the basis for determining the proposed[11] criteria for minimum image quality that would need to be present in a rearview image in order for a driver of average vision to have the ability to discern child-sized obstacles located within the field of view. Test procedures that were proposed in the NPRM for assessing a rearview image's compliance with the asserted criteria are described. Finally, the proposed test procedures is demonstrated by applying them to six 2010-2011 model year vehicles equipped with original equipment rearview video system.

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[7] Cameron Gulbransen Kids Transportation Safety Act of 2007, (Pub. L. 110–189, 122 Stat. 639–642), § 4 (2007).

[8] Rearview images sizes examined included 2.4 inches (measured diagonally), 3.5 inches, and larger sizes. Test results showed that the reduction in crashes with an unexpected rear obstacle for the 3.5-inch image system (48 percent) was nearly twice that seen with a 2.4-inch image (26 percent) system or ultrasonic sensors (25 percent).

[9] 75 FR 76186, December 7, 2010

[10] A different size of field of view behind a vehicle may be necessary to aid a driver in avoiding other types of backing crashes.

[11] 75 FR 76186, December 7, 2010

2.0 DETERMINING IMPROVED VEHICLE REAR VISIBILITY NEEDS

This section provides additional details regarding the analyses summarized in the December 2010 FMVSS No. 111 NPRM[12] that provided the basis for proposed improved vehicle rear visibility requirements.

2.1 Relationship Between Pedestrian Location and Backover Risk

To better understand the importance of rearview image fields of view providing the driver with visibility of specific areas behind the vehicle, Monte Carlo simulation was used to estimate the risk to a pedestrian at a specific location at the start of a backing maneuver.

Important assumptions were made about the behavior of the driver and the pedestrian for this analysis. The vehicle and pedestrian were assumed to begin moving at the same time and were assumed to be unaware of each other. Therefore, the motions of the vehicle and pedestrian were independent of the each other. In this analysis, it was possible for the pedestrian to walk or run into the vehicle. If the impact was with the rear of the vehicle, a backover incident was considered to have resulted. If the impact was with the side or front of the vehicle, the crash was not counted as a backover crash for the purposes of this analysis.

2.1.1 Vehicle Descriptors

Several descriptors were used to define the simulated vehicle in this analysis. The width of the vehicle was assumed to be 6.0 ft for this analysis. The distance that the vehicle backed up during each backing trial was determined by a random draw from a three-parameter Weibull probability distribution[13] for distance backed that was based on data from the *On-Road Study of Drivers' Use of Rear Video Systems* (ORSDURVS) study[14].

The ORSDURVS study observed driver's use of rearview video systems during staged and naturalistic backing maneuvers to determine whether drivers look at the rearview video system's display during backing and whether use of the system affects backing behavior. The 37 test participants aged 25 to 60 years were comprised of 12 drivers of rearview video equipped vehicles, 13 drivers of vehicles equipped with a rearview video system and a rear parking sensor system, and 12 drivers of vehicles having no backing aid.

All ORSDURVS study participants had driven and owned a 2007 Honda Odyssey minivan as their primary vehicle for at least 6 months. Participants visited the sponsor's research lab to have unobtrusive video and other data recording equipment installed in their personal vehicles and take a brief test drive. Participants then drove their vehicles for a period of four weeks in their normal daily activities while backing maneuvers were recorded. At the end of the four weeks, participants returned to the research lab to have the recording equipment removed. Participants

[12] 75 FR 76186, December 7, 2010

[13] See Grygier, P. A., Garrott, W. R., and Mazzae, Elizabeth N., *Measured and Calculated Useful Fields of View of Rear-Mounted Convex Mirrors*; NHTSA report, publication pending, National Highway Traffic Safety Administration, in press, for additional information about the Weibull probability distributions used.

[14] Mazzae, E. N., Barickman, F. S., Baldwin, G. H. S., and Ranney, T. A., *On-Road Study of Drivers' Use of Rearview Video Systems (ORSDURVS)*, National Highway Traffic Safety Administration, DOT 811 024, 2008.

took a second test drive, identical to the first, except that when backing out of the garage bay at the end of the drive, an unexpected obstacle appeared behind the vehicle.

During the ORSDURVS study naturalistic backing maneuvers, the 37 participants made 6,145 backing maneuvers. The minimum distance the vehicle backed was 1.38 ft, the average distance 35.2 ft, and the maximum distance 294.3 ft.

To simplify the current analysis, the Monte Carlo simulation assumed that the vehicle backed up at a constant speed based on a random draw from a three-parameter Weibull probability distribution also based on ORSDURVS study[15] data. During the ORSDURVS study, drivers' average backing speed during naturalistic backing maneuvers was 2.26 miles per hour, the minimum backing speed was 0.4 mph, and the maximum speed 7.8 mph.

Because it was assumed that long backing maneuvers more frequently involve turning than do short ones, any backing trial with more than 25.5 ft of backing was assumed to possibly include a turn. To determine whether the vehicle turned to the left, went straight, or turned to the right during each backing trial, a uniformly distributed random number was drawn. There was a 25-percent probability of a left turn, a 25-percent probability of a right turn, and a 50-percent probability of no turn. The turn, if there was one, did not commence until after 25.5 ft of backing. Once turning commenced the rear bumper of the vehicle traveled around a 20-ft radius circle. Because the maximum distance in the turn was 30 ft, the angle through which the vehicle turned ranged from 0 to 86 degrees.

2.1.2 Pedestrian Descriptors

The pedestrian was modeled in the horizontal plane as a circle of radius 0.75 ft. To simplify the analysis, the pedestrian was assumed to move at constant speed and direction. The angle of pedestrian travel was determined by a random draw from a uniform probability distribution extending from -180.0 to +180.0 degrees. The pedestrian was stationary 33 percent of the time. The remaining 67 percent of the time, the pedestrian's walking speed was determined by a random draw from a three-parameter Weibull probability distribution. The pedestrian's minimum speed was 0.6 mph, his average speed 1.2 mph, and his maximum speed 1.8 mph.

To define the position of the pedestrian behind the vehicle, axes were assigned to the grid. An X axis was set up pointing straight back along the longitudinal centerline of the vehicle with its origin at the rear bumper of the vehicle. A Y axis was set up pointing along the (assumed straight) rear edge of the rear bumper with its origin at the center of the rear bumper. Positive Y values were on the driver's side of the vehicle. The pedestrian was always started at the center of one of the one foot grid squares. All possible initial pedestrian positions were simulated. Therefore, initial pedestrian X positions ranged from -19.5 to 89.5 ft in one foot increments. Similarly, the initial pedestrian Y positions ranged from -34.5 to 34.5 ft also in one foot increments.

[15] Ibid.

2.1.3 Additional Simulation Information

A total of 200,000 Monte Carlo simulation trials were run with the pedestrian initially in the center of each square. Each trial simulated 60.0 seconds of time unless the pedestrian collided with the vehicle or the vehicle completed its movement first. Actual backing events do not typically last for 60.0 seconds. The longest backing event out of the 6,185 in the ORSDURVS[16] data set was 52.8 seconds long. For the simulation, both the backing distance and average backing speed were determined independently of each other from Weibull probability distributions. This relationship is not so simple in the real world, as statistical analyses of the ORSDURVS data set indicates that for real driving, backing distance increases along with average backing speed. However, for the purposes of this effort to accept the independence of the backing distance and average backing speed so as to simplify the simulation. As a result, 1.1 percent of all simulated backing trials had not been completed after 60.0 seconds of simulation. Also for the purposes of this analysis it was decided that the normalization process would adequately account for not otherwise dealing with the issue of long backing maneuvers.

A count was made of all trials for which the pedestrian collided with the rear bumper of the vehicle. If the pedestrian collided first with either the front or sides of the vehicle, then this was not counted as a backing collision.

After completion of the simulation for all grid squares, a normalization of the backing crash counts for each grid square was performed. The normalization converted each grid square's crash count into its probability of crash relative to the number of trials for that square. The grid squares for which a crash was most likely to occur were the two directly behind the bumper in the center of the vehicle.

Figure 1 summarizes the simulated relative backover crash risk for each grid square. The risk numbers on the grid are shown to only one significant figure (the remaining decimal places were dropped). For example, a risk of 0.4 represents a risk of at least 0.4 but less than 0.5.

The output of this analysis calculated relative crash risk values for each grid square representing a location behind the vehicle. Analysis results showed that the probability of crash decreases rapidly as the pedestrian's initial location is moved rearward, away from the rear bumper of the vehicle. Areas located behind the vehicle and to the side were also shown to have moderately high risk, giving pedestrians some risk of being hit even though they were not initially directly behind the vehicle. The results suggest that an area 16 ft wide by 39 ft long centered behind the vehicle would address all pedestrian locations having relative crash risks of 0.10 and higher. To address crash risks of 0.20 and higher, an area 10 ft wide and 32 ft long centered behind the vehicle would need to be covered. The analysis showed that an area covering approximately the width of the vehicle out to a range of 15 ft would encompass risk values of 0.40 and higher.

[16] Mazzae, E. N., Barickman, F. S., Baldwin, G. H. S., and Ranney, T. A., *On-Road Study of Drivers' Use of Rearview Video Systems (ORSDURVS)*, National Highway Traffic Safety Administration, DOT 811 024, 2008.

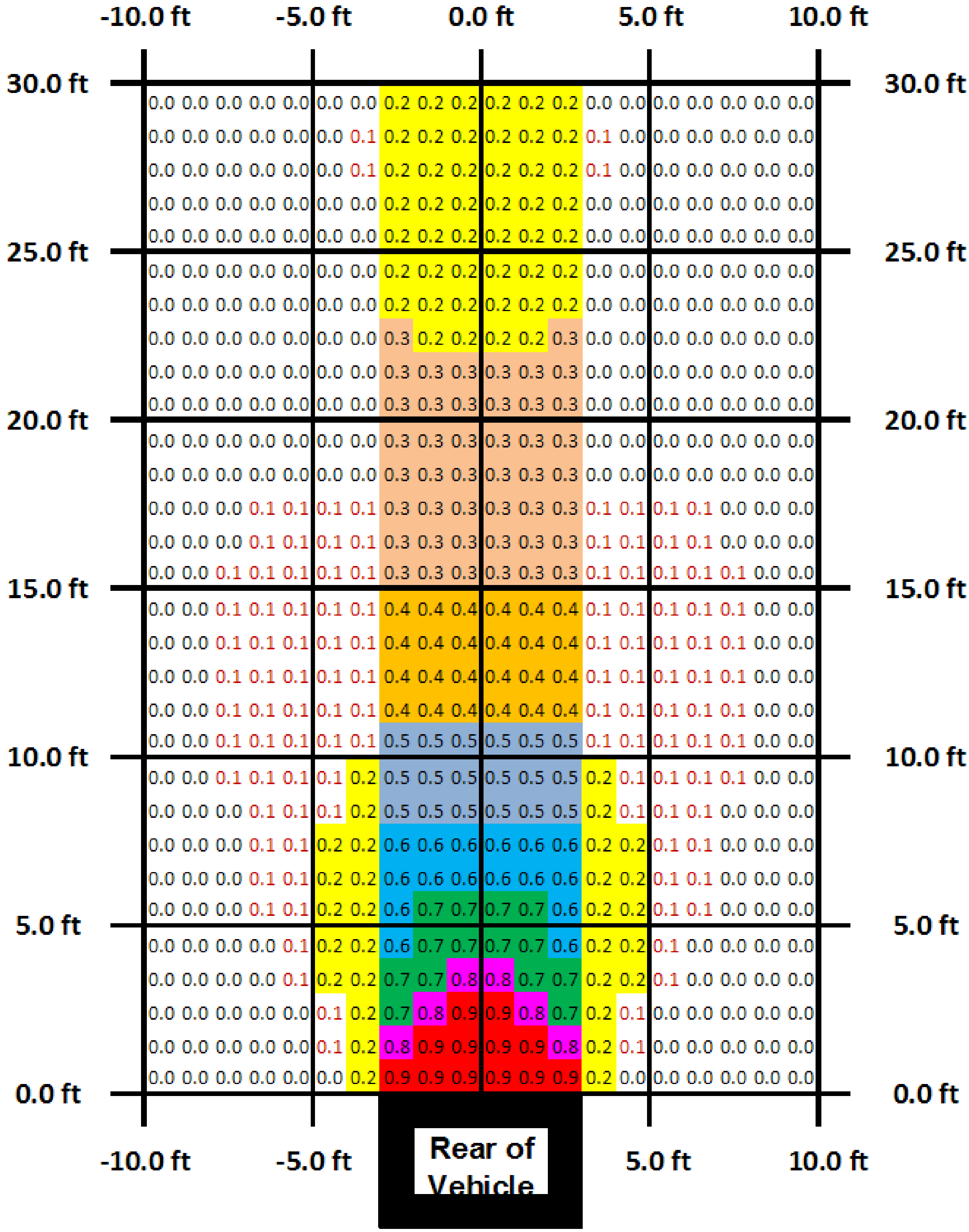

Figure 1. Summary of Simulated Relative Backover Crash Risk as a Function of Position

2.2 Determining Rearview Image Field of View Size

To determine a minimum width of a field of view that may be appropriate for preventing backover crashes, NHTSA Special Crash Investigation's (SCI) backover case data and Monte Carlo analysis of backover crash risk as a function of pedestrian initial location were examined. Only the Monte Carlo analysis was used to estimate the lateral threat zone while both SCI backover case data and Monte Carlo analysis were used to establish the longitudinal threat zone.

First, the lateral threat zone from Monte Carlo analysis was estimated. As Figure 1 shows, elevated risk levels greater than 0.1 exist as far as 8.0 feet laterally to the left and right of a rearward extension of a vehicle's longitudinal centerline. However, the higher risk zone (risk levels greater than 0.2) are concentrated within a 10.0 feet wide area that extends symmetrically 5.0 feet laterally to either side of the extended vehicle centerline. Accordingly, the NPRM specified as the desired width of the area of improved rear visibility this area of 10.0 feet (3.05 meters) wide that is centered on the vehicle's centerline.[17]

To determine the appropriate minimum longitudinal range (i.e., length) of the area that should be specified to maximize the feasibility and effectiveness of the proposal in reducing backover crashes, NHTSA considered comments on the Advanced Notice of Proposed Rulemaking that was published in the Federal Register on March 4, 2009[18], SCI backover case data, and the results of our Monte Carlo analysis. Using the 58 SCI backover cases, NHTSA examined the distance the vehicle traveled prior to striking the pedestrian. Figure 2, which was presented in the NPRM[19], shows the percent of cases encompassed by various ranges of longitudinal distance. These data show that in 77 percent of SCI backover cases the vehicle traveled 20.0 feet or less before striking the victim. In comparison, the just described Monte Carlo analysis of backover crash risk as a function of the pedestrian's initial location indicated that the highest risk for pedestrians being struck is within a range that extends 32.0 feet aft of the rear bumper. Given that the SCI data represent actual crashes, the NPRM proposed a 20-foot longitudinal range (extending backward from the rearmost point of the vehicle's rear bumper) for rear visibility.

[17] 75 FR 76186, December 7, 2010

[18] U.S. Department of Transportation, National Highway Traffic Safety Administration, 49 CFR Part 571, Docket No. NHTSA-2009-0041, RIN 2127-AK43, Federal Motor Vehicle Safety Standard; Rearview Mirrors, Federal Register /Vol. 74, No. 41/, Pages 9478 – 9520.

[19] 75 FR 76186, December 7, 2010

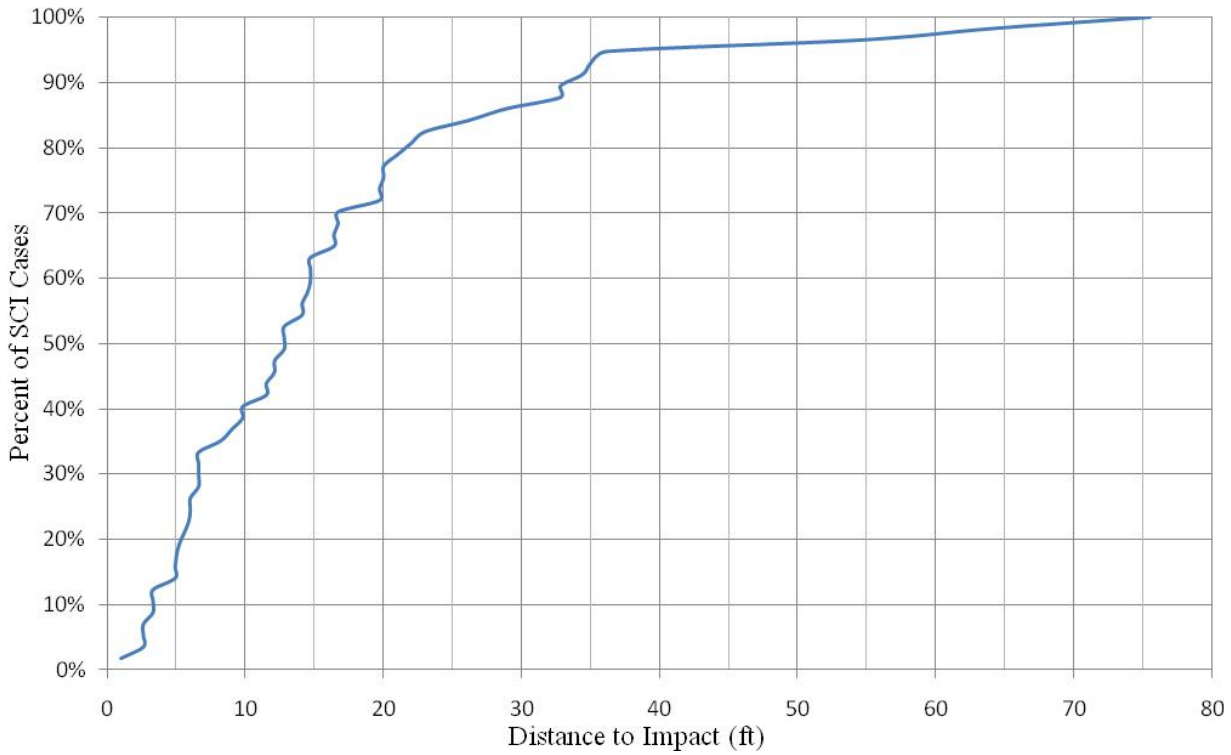

Figure 2. Percent of SCI Backover Cases as a Function of Distance to Impact

In summary, if a driver can see a good-quality image of the 10.0 feet (3.05 meters) wide by 20.0 feet (6.10 meters) long area in which a majority of backover crash victims have been located, the majority of backover crashes could be preventable. Therefore, this field of view was selected for use in evaluating rearview images in this research.

Given the size and geometry of this area, a view of the entire area should be obtainable through the installation of a single video camera that is located at or near the centerline of the vehicle.

To ensure adequate visibility of this area, the procedure used in this work involved outlining the field of view using seven test objects (cylinders) as shown in Figure 3. The testing described here assumed that if these cylinders could be seen in the rearview image, then the entire enclosed area could also be seen in the image.

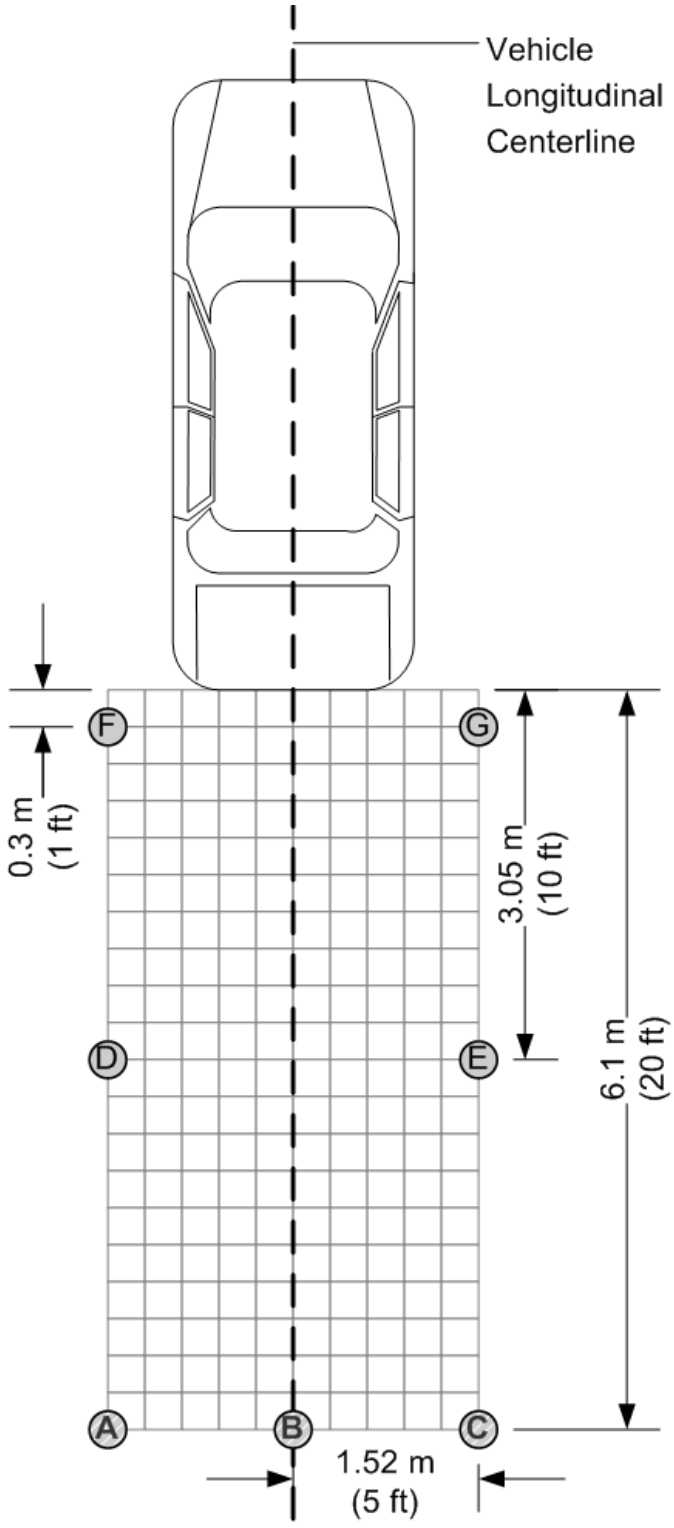

Figure 3. Cylinder Test Object Locations

For school bus cross-view mirrors, FMVSS No. 111 requires that the entire top surface of each cylinder must be visible. However, due to the potential for rearview video cameras to be mounted at heights of less than 32 inches on some compact cars and sporty vehicles, NHTSA proposed in a December 2010 Notice of Proposed Rulemaking an alternative detection criterion for this test. For test objects located 10 or more feet aft of the vehicle's rear bumper, the entire height and width of each test object must be visible. This criterion equates to the driver being able to see the entirety of an average sized 18-month-old child and serves to ensure that detection of such a child, if present, between 10 and 15 feet behind the vehicle is possible.

Due to the approximately conical shape of the volume captured by the video camera's curved lens, only a portion of a child or child-sized object in close proximity to the rear bumper may be visible, particularly at the edges of the camera's viewing angle. To ensure that at least a portion of test objects 'F' and 'G' (in Figure 6) may be visible in a rearview image, the test procedure outlined here positions them 1 foot aft of the rear bumper face. To ensure that the driver has enough information to be able to discern whether an "object," such as a child, is present, it is important to indicate how much of the test objects must be visible. Seeing a child's face or another body area of similar size would likely result in successful visual recognition of the child by the driver. The average breadth of an 18-month-old child's head is stated to be 5.9 inches (150 mm).[20] Based on this, it was asserted that in order to give the driver the best opportunity to identify an object or child in close proximity to the rear of the vehicle, a 5.9-inch (150 mm) wide portion of the test object should be visible at some point along the height of both F and G.

2.3 Establishing Rearview Image Quality Criteria

Image quality measurements assess whether a rearview image provided to a driver will enable the driver to discern objects within the displayed field of view. Image quality in this context was based on the apparent angular size (i.e., visual angle subtended) of a test object having a known actual size and location. The visual angles subtended by test objects as part of this test procedure were calculated using (1) the distance between the rearview image and a camera, mounted so as to represent the view observable by a 50th-percentile height male driver and (2) the test object's linear dimensions as seen in a photograph of the rearview image. Details of the calculation procedure are provided in Section 3.4. The following criteria for adequate image quality based on the apparent angular size of each test object were asserted in the NPRM:

1. When the apparent angular size of the three test cylinders that were located 20.0 feet aft of the rearmost point on the vehicle's rear bumper (Cylinders A, B, and C in Figure 3) are measured, the average apparent angular size of the three must not be less than 5 minutes of arc when viewed in the rearview image.
2. When viewed in the rearview image, the apparent angular size of each individual test cylinder must not be less than 3 minutes of arc.

There is no need for image quality criteria based on the apparent angular size for any of the nearer test objects, since the geometry of the test object arrangement ensures that the three furthest test objects will always appear to be the smallest, thus representing the worst case for

[20] The 5.9 in (150 mm) dimension is the average breadth of an 18-month-old child's head per Center for Disease Control's "Clinical Growth Charts, Birth to 36 months: Boys; Length-for-age and Weight-for-age percentiles" and "Clinical Growth Charts, Birth to 36 months: Girls; Length-for-age and Weight-for-age percentiles," published May 30, 2000 (modified 4/20/2001).

visibility among the seven cylinders.[21] The reasons for the above listed criteria are discussed in the remainder of this section.

One measure of *visual acuity* is the ability of the human eye to distinguish a pattern of alternating black and white stripes of equal width as stripes instead of a solid gray block. The maximum number of distinguishable black/white pairs may be expressed in *cycles per degree*. "*For a human eye with excellent acuity, the maximum theoretical resolution is 50 CPD*[22]." This is equivalent to stating that the minimum detectable angle is

60 minutes/degree ÷ 50 cycles/degree = *1.2 minutes of arc*

However, many drivers do not have excellent visual acuity. A survey of driver's licensing requirements by state shows that visual acuity of drivers without corrective lenses of 20/40 to as low as 20/60 in some states is sufficient to obtain an unrestricted driver's license. Furthermore, when driving a vehicle, drivers have to do more than distinguish a pattern of alternating black and white stripes of equal width as stripes instead of a solid gray block – they have to be able to make judgments about the nature of the object in sight. In 1983, Satoh, Yamanaka, Kondoh, Yamashita, Matsuzaki, and Akisuzuki[23] examined the relationship between an object's subtended visual angle[24] at a person's eyes and a person's subjective ability to see the object and to make judgments about what he or she is seeing. This research by Satoh et al. indicated that 5 minutes of subtended arc was the minimum size for an average person to be able to make judgments about an object and 3 minutes of subtended arc was the limit below which the average person could not see an object.

In the past, NHTSA has based its requirements for minimum image size (the minimum subtended visual angle at the driver's eyes) on the 3 minutes of subtended arc limit in the Satoh et al. research.[25] For example, the school bus cross-view mirror requirements in FMVSS No. 111 for minimum apparent angular size are based on the Satoh research. Section S9.4 of FMVSS No. 111[26] requires, for the worse case test object, Cylinder "P", that a school bus cross-view mirror show the driver a specified child surrogate test object located at a specified location with a subtended visual angle of at least 3 minutes of arc.

The December 2010 NPRM[27] illustrated the rationale for requiring a minimum subtended visual angle at the driver's eyes of at least 5 minutes of arc (on the average) in the current case instead of the 3 minutes of arc used in the school bus mirror requirements for the following reasons:

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[21] For the optical characteristics of the types of technologies anticipated for use in this application.
[22] Russ, J.C., *The Image Processing Handbook*, CRC Press, 2006.
[23] Satoh, H., Yamanaka, A., Kondoh, T., Yamashita, M., Matsuzaki, M., and Akisuzuki, K., "Development of a Periscope Mirror System," JSAE Review, 1983.
[24] The angle which an object or detail subtends at the point of observation; usually measured in minutes of arc. If the point of observation is the pupil of a person's eye, the angle is formed by two rays, one passing through the center of the pupil and touching one edge of the observed object and the other passing though the center of the pupil and touching the opposite edge of the object.
[25] Garrott, W. R., Rockwell, T. H., and Kiger, S. W., *Ergonomic Research on School Bus Cross View Mirror Systems*, National Highway Traffic Safety Administration, DOT 807 676, 1990.
[26] 49 CFR 571.111, Standard No. 111, Rearview mirrors.
[27] 75 FR 76186, December 7, 2010

> "First, school bus drivers must be specially licensed before they can drive a school bus carrying children. They are required to obtain a Commercial Drivers License with a School Bus Endorsement. The training required to obtain this special license and the necessity of being vigilant in all types of crashes in order to retain their license and employment is expected to increase school bus drivers' awareness of the possibility of pedestrians suddenly entering danger areas around their bus. The combined effect of this training and the necessity for attentiveness is expected to encourage drivers to pay more attention to small images that are visible in a bus's convex mirrors.
>
> Second, school bus drivers are specifically trained in the use of their bus's convex cross-view mirrors. In the late 1980's, when the school bus cross-view mirror requirements of FMVSS No. 111 were being developed, 49 states plus Washington, DC[28] required annual training for all school bus drivers in the use of their bus's cross-view mirrors. This training is expected to allow drivers to make better use of very small images that they see in the convex mirrors.
>
> Third, school bus cross-view mirrors are intended to be used before the bus begins to move, while the bus is stationary. As a result, drivers can take as much time as they need to determine what they see in their bus's cross-view mirrors. In contrast, in the passenger vehicle environment, drivers may use the display while the vehicle is stationary and while the vehicle is in motion backing up (albeit at fairly low speeds). As a result, drivers may have limits on the amount of time that they may use to determine what they are seeing in a rearview video display. Again, this argues for a larger minimum image size requirement."

In summary, as stated in the December 2010 NPRM[29], a stronger requirement may be more appropriate for passenger vehicles since their drivers do not have the same vehicle and system (e.g., mirror use) training as school bus drivers do, nor do passenger vehicles typically use the systems in a stationary scenario. Based on this, the Satoh-recommended 5 minutes-of-arc subtended visual angle requirement was proposed in the NPRM.

Testing (performed in parallel with the current study and not described in this report) was performed with a 2007 Honda Odyssey minivan fitted both with an original equipment (from a 2008 Honda Odyssey) 2.4-inch diagonal rearview video display and an original equipment 3.5-inch diagonal rearview video display (from a vehicle of a different manufacturer). Testing results are described in the short NHTSA docket report "Drivers' Use of Rearview Video and

[28] California had no such requirement.
[29] 75 FR 76186, December 7, 2010

Sensor-Based Backing Aid Systems in a Non-Laboratory Setting."[30] Driver performance detecting a child surrogate while backing was substantially worse when the Odyssey was equipped with a 2.4-inch diagonal rearview video display than when it was equipped with a 3.5-inch diagonal rearview video display. This result demonstrates that drivers performed better when the displayed test object subtended 5 minutes of arc instead of 3 minutes of arc since for both displays the child surrogate subtended more than 3 minutes of arc but only for the 3.5-inch diagonal display did the child surrogate subtend 5 minutes of arc. For this vehicle, a 2.8-inch or larger (measured diagonally) rearview image presented in the interior rearview mirror is necessary to meet the 5 minutes of arc requirement.

Performance of subtended visual angle measurement in related work[31] demonstrated that up to approximately ±2 minutes of arc of experimental noise may be seen in individual test object measurements. Such noise can stem from inaccuracies in cylinder width measurements stemming from low image resolution (resulting from video camera and/or LCD resolution) as well as less than perfect measurement reliability (humans measure the photos so there is some subjectivity involved, especially if cylinders appear blurry in the photo). To compensate for this experimental noise, the measurements of the three test cylinders are averaged. By averaging these values, the expected measurement error is reduced to less than 1.2 minutes of arc. The 5 minutes of arc minimum size requirement was applied to only the average value of the three of the rearmost test cylinders. For each individual cylinder, a 3 minutes of arc limit is applied (desired limit of 5 minutes of arc minus up to 2 minutes of arc due to experimental noise gives an actual limit of 3 minutes of arc).

[30] Mazzae, E. N., *Drivers' Use of Rearview Video and Sensor-Based Backing Aid Systems in a Non-Laboratory Setting*, Document ID: NHTSA-2010-0162-0001, Docket ID: NHTSA-2010-0162, 2010.

[31] Grygier, P. A., Garrott, W. R., and Mazzae, Elizabeth N., *Measured and Calculated Useful Fields of View of Rear-Mounted Convex Mirrors*; NHTSA report, publication pending.

3.0 TEST METHOD

This section describes how the developed measurement procedures are carried out for the assessment of rearview image field of view and image quality.

3.1 Preparations for Rearview Image Measurements

Vehicles to be measured were prepared according to these conditions to ensure consistency of test conditions and vehicle pitch.

- Test vehicle fuel tanks were filled to capacity in order to provide a consistent fuel level across vehicles.
- Vehicle tires were verified to be of the original equipment size and were inflated to the manufacturer's recommended inflation pressure values.
- Vehicle windows were cleaned, cleared of any obstructions such as window stickers, and were fully closed during testing.
- Each vehicle was loaded to simulate the weight of the driver and four passengers (or the designated occupant capacity, if less), at an average weight of 68 kg per occupant (including the driver).

Each test vehicle was positioned on a flat, level, indoor test grid marked with 1-foot squares and a reference coordinate system**.** The vehicle was driven onto the grid and positioned with the rear bumper flush with the 0.0-foot line and the vehicle centerline directly above the longitudinal axis of the test grid. The vehicle's position on the test grid was confirmed using a plumb bob hung from the trunk or rear hatch latching mechanism at the vehicle's centerline as a reference point. Wheeled jacks may be used to maneuver the vehicle and adjust its position on the grid by lifting the vehicle off the floor surface so the vehicle could be pushed into position. Once positioned accurately on the grid, the vehicle is lowered into place and the jacks removed.

Before photographs were taken, a ruler was affixed to the base of the rearview image screen such that it was level with the ground. The ruler was included in the photo frame to be used for a scaling factor (s) when objects in the photo are measured. The ruler should have a matte finish so as not to cause reflections when taking the data photograph.

3.2 Reference Eyepoint Determination

The reference eyepoint is intended to simulate the location of a 50th percentile male driver's eyes (rather than the 95th-percentile male used in existing FMVSS No. 111 rearview mirror requirements) when looking at the rearview image. The eyepoint of a 50th-percentile male driver was chosen for use in this work to represent a midpoint of driver size.

Based on observations of drivers using rearview video systems in NHTSA testing[32], for visual displays located in the vicinity of the center console or interior rearview mirror, the driver will typically turn his or her head to look at the display with little or no lateral eye shift. Therefore, to estimate the location of the driver's eyes when looking at a rearview image, the forward-looking eyepoint of the driver was simulated to rotate toward the centerline of the vehicle as though the driver is turning his or her head toward the image. Anthropometric data from a NHTSA-

[32] Mazzae, E. N., Barickman, F. S., Baldwin, G. H. S., and Ranney, T. A., *On-Road Study of Drivers' Use of Rearview Video Systems (ORSDURVS)*, National Highway Traffic Safety Administration, DOT 811 024, 2008.

sponsored study of the dimensions of 50th percentile male drivers seated with a 25-degree seat back angle ("Anthropometry of Motor Vehicle Occupants"[33]) give the longitudinal and vertical location, with respect to the H point, of the left and right infraorbitale (a point just below each eye) and the head/neck joint center (J) at which the head rotates about the spine. Given an average vertical eye diameter of approximately 0.96 inch (24 mm), the center of the eye is located 0.48 inches (12 mm) above the infraorbitale. By determining the midpoint of the lateral locations of the driver's eyes, a point is obtained which resides in the mid-sagittal plane (the vertical/longitudinal plane of symmetry of the human body) of the driver's body. This point is referred to in this work as the eye midpoint and is denoted by 'M_f'. Using the point at which the head rotates (J), M_f can be rotated toward the rearview image to obtain a new eyepoint, M_r, which serves as the test reference point representing the location of the midpoint of a 50th percentile male driver's eyes when the head is turned to look at a rearview image. These points are illustrated in Figure 4.

[33] Schneider, L. W., Robbins, D. H., Pflüg, M. A. and Snyder, R. G., *Anthropometry of Motor Vehicle Occupants; Volume 1 – Procedures, Summary Findings and Appendices*, National Highway Traffic Safety Administration, DOT 806 715, 1985.

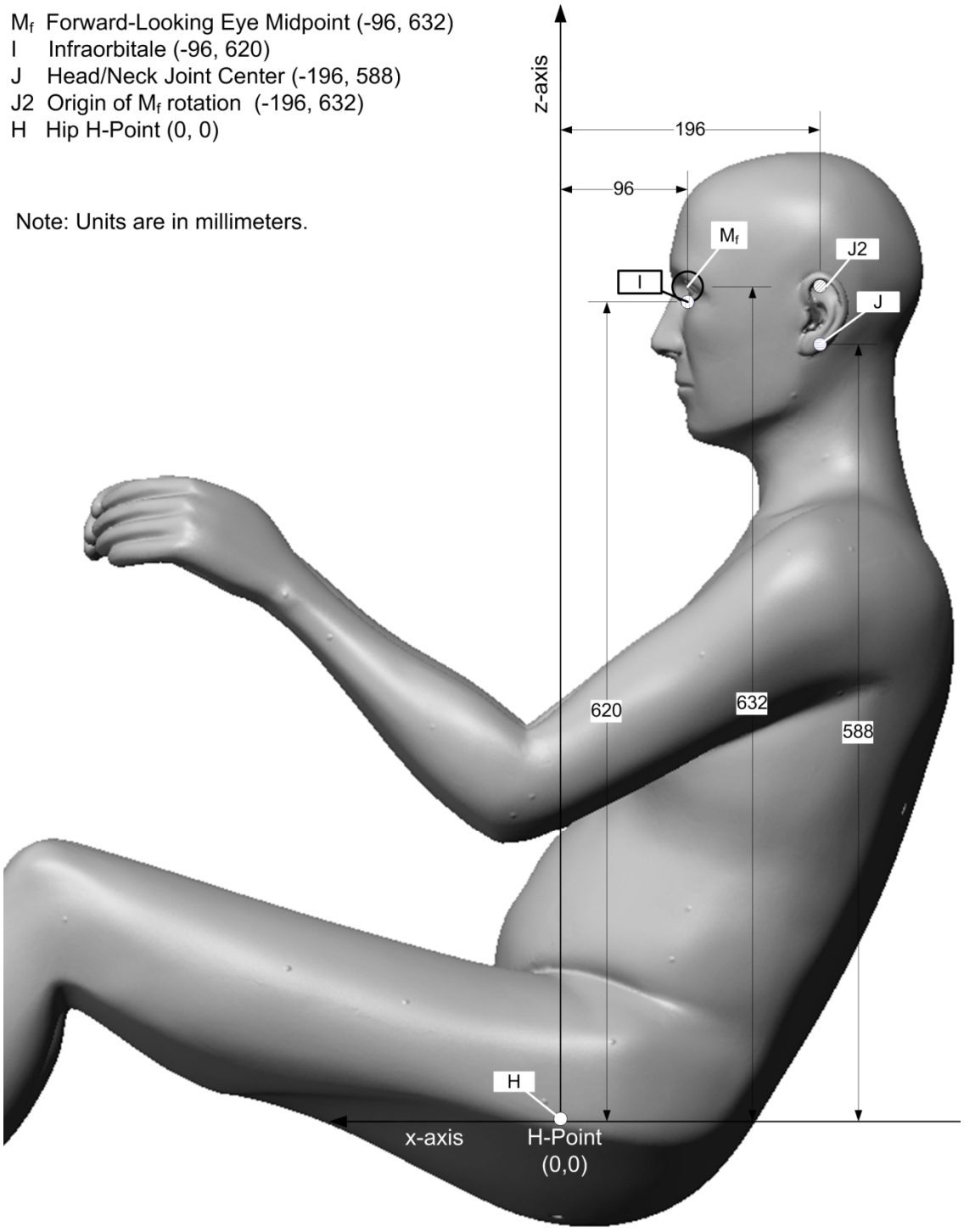

Figure 4. Coordinates of the Forward-Looking Eye Midpoint (Mf) and Joint Center (J) of Head/Neck Rotation of a 50th Percentile Male Driver with respect to the H-Point (H) in the Sagittal Body Plane.

For measurements performed in this work, each vehicle's driver's seat was adjusted to the midpoint of its longitudinal adjustment range and to the lowest point of the vertical adjustment range. An H-Point machine was installed in the vehicle driver's seat per the installation procedure outlined in SAE J826[34]. An image quality measurement fixture, described in detail in Appendix 1, and a camera attached to the H-Point machine as shown in Figure 5. The driver's seat seatback angle was adjusted to 25 degrees[35] at the vertical portion of the H-Point machine's torso weight hanger. If a seatback angle of 25 degrees was not selectable due to the location of seatback angle detents for a particular test vehicle, the seatback angle position corresponding most closely to 25 degrees was used. Once the seat was properly adjusted, the camera and fixture were adjusted to simulate the geometry of a driver's head turning to look at a rearview image. Specifically, the point M_f was rotated about the head/neck rotation point (J2) until the camera lens was pointed at an angle corresponding to the lateral position of the rearview image. This new, rotated location of M_f was referred to as M_r. Lastly, the camera was rotated about a horizontal axis containing M_r to create pitch that served to simulate the driver's eyes looking upward or downward as needed to cause the line of sight to intersect with the center of the rearview image (which might be mounted higher or lower than M_r. No head pitch was simulated as it was assumed to be unlikely or negligible.

Figure 5. Rearview Image Measurement Fixture

[34] SAE J826, *Devices for Use in Defining and Measuring Vehicle Seating Accommodation,* Rev. JUL95, Society of Automotive Engineers, 1995.
[35] SAE J826, *Devices for Use in Defining and Measuring Vehicle Seating Accommodation,* Rev. JUL95, Society of Automotive Engineers, 1995.

To facilitate calculation of image quality, the distance (*d*) from the rotated eyepoint (M_r) to the center of the rearview image screen was determined. This viewing distance is a factor in the formula for calculating the subtended visual angle of the test objects in this procedure.

To determine the viewing distance as accurately as possible, a measurement is made from the center of the rearview image to a point inside the camera lens which is the center of the camera's CCD chip (the "image plane"). Measurements were taken from the center of the rearview image display to an external point on the side of the camera that lies on a plane containing that focal point, with the plane being parallel to the rearview image screen. This provided an approximate distance measurement. Using the Pythagorean Theorem and the distance from the external point on the side of the camera to the focal point inside the camera, the approximate distance measurement was corrected to yield an accurate value for *d*.

Figure 26 shows the geometry of the situation and defines the symbols used.

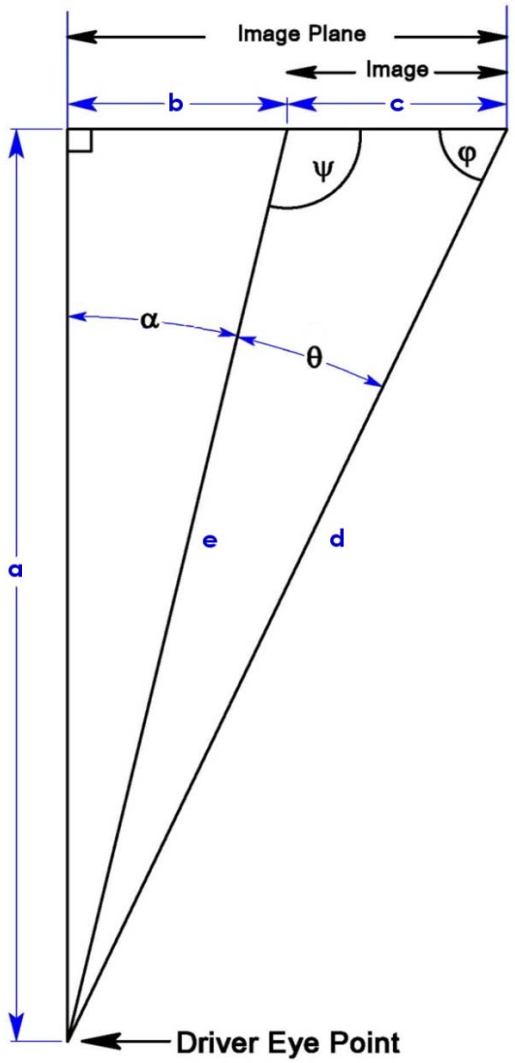

Figure 6. Geometry Used to Derived Subtended Visual Angle Equation

3.3 Rearview Image Field of View Test Procedure

A test procedure was developed to ensure that a rearview image provided to the driver covers a sufficiently large area behind the vehicle (described in this section).

The test procedure used in this research to measure the rearview image field of view is similar to that currently used for school bus mirrors[36]. Like the school bus mirror test, the current test procedure used a large format camera placed with the imaging sensor located at the "reference eyepoint" (see Section 3.2). A matte finish ruler affixed beneath the visual display and aligned laterally along the bottom edge of the visual display provided a reference for scaling purposes in the image quality portion of the test procedure (see Section 3.4).

To demonstrate that a rearview image provides a field of view large enough to permit a driver to view obstacles and pedestrians over an area known to be related to backover crashes, the perimeter of a minimum visible area was outlined. Seven test objects (cylinders), represented by black circles in Figure 3 were used to outline the visible area of interest. Each test object was a cylinder 12.0 inches (305 mm) in diameter and 32.00 inches (813 mm) tall. The three rearmost test objects (Cylinders A, B, and C in Figure 6) had a horizontal band encircling the top 5.9 inches (150 mm). The color of the band was chosen to have high contrast with respect to the coloring of the rest of the cylinder. The centerlines of Cylinders A and C were located 5.0 feet (1.52 meters) laterally and 20.0 feet (6.10 meters) longitudinally from the center of the vehicle's rear bumper, with Cylinder B located between them along the centerline of the vehicle. The two test objects closest to the vehicle (Cylinders G and F) had a 5.9-inch (150 mm) wide vertical stripe spanning the full height of the cylinder. The coloring vertical stripe also was selected to have high contrast with respect to the coloring of the rest of the cylinder. The cylinders and their markings are pictured in Figure 7.

[36] 49 CFR 571.111, Standard No. 111, Rearview mirrors, Section 13: School bus mirror test procedures.

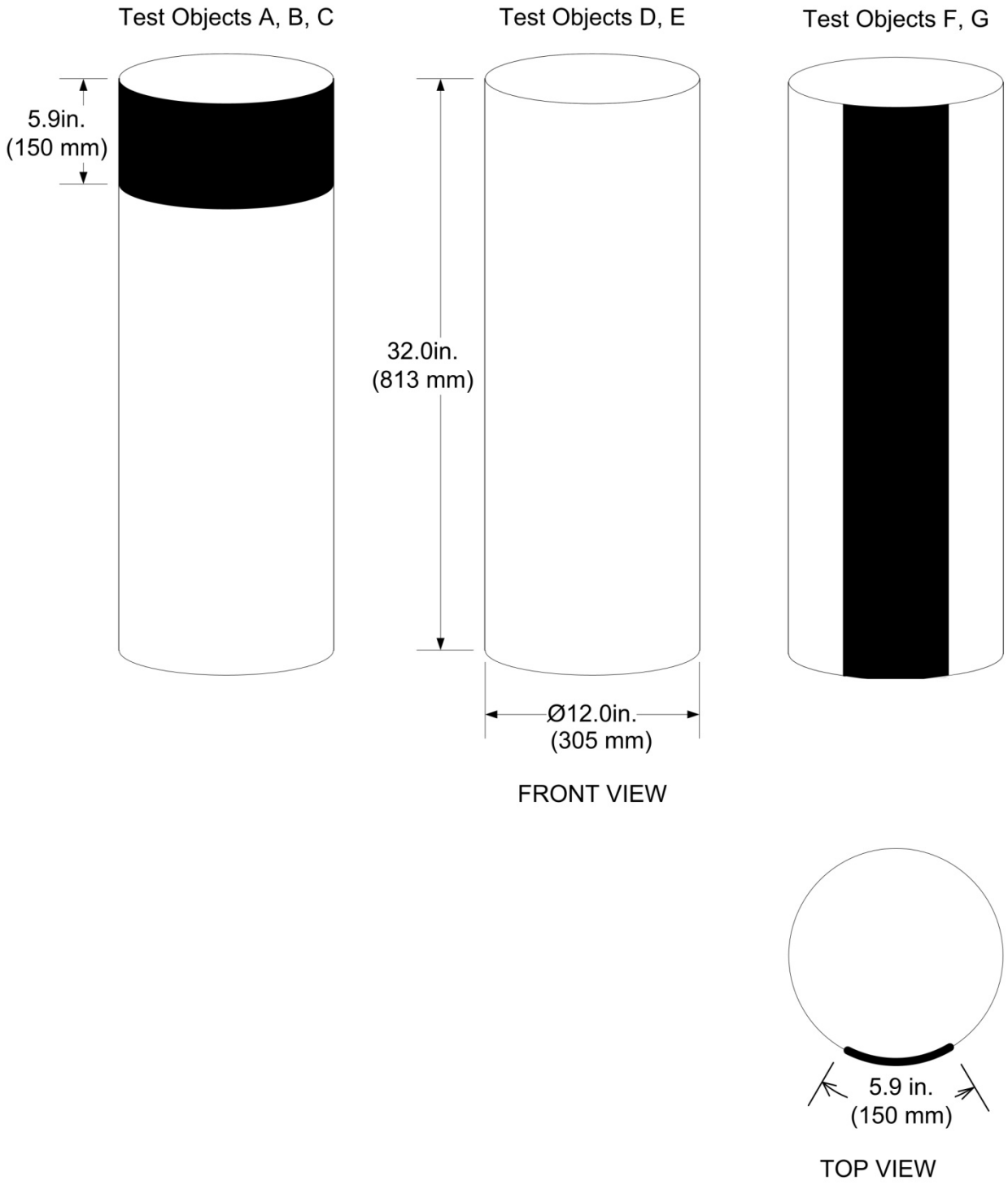

Figure 7. Test Object Dimensions and Markings

The cylinders are pictured in their test positions as displayed in a rearview image in Figure 8. The centerlines of Cylinders F and G were located 5.0 feet (1.52 meters) laterally from the center of the vehicle's rear bumper and 12.0 inches (305 mm) longitudinally aft of the rearmost point of the bumper face with the contrasting stripe oriented toward the vehicle's video camera. Between these sets of cylinders, the centerlines of Cylinders D and E were located 5.0 feet (1.52 meters) laterally and 10.0 feet (3.05 meters) longitudinally from the center of the vehicle's rear bumper.

Figure 8. Test Object Arrangement as Displayed in Rearview Image

For school bus cross-view mirrors, FMVSS No. 111 requires that the entire top surface of each cylinder must be visible. However, given that rearview video cameras (or other image sensing equipment) installed on some compact cars and sporty vehicles may be mounted at heights of less than 32.00 inches (813 mm), the tops of the test cylinders may not be visible in the rearview images of these vehicles. For test objects located 10.0 feet (3.05 meters) or more aft of the vehicle's rear bumper, the criterion used in this research was that the entire height and width of each test object should be visible. This criterion equates to the driver being able to see the entirety of an average sized 18-month-old child and serves to ensure that detection of such a child, if present, between 10 and 15 feet behind the vehicle is possible.

Due to the approximately conical shape of the volume captured by the video camera's curved lens, only a portion of a child or child-sized object in close proximity to the rear bumper may be visible, particularly at the edges of the camera's viewing angle. To ensure that at least a portion of Cylinders F and G (in Figure 3) are visible, the test procedure positioned these cylinders 12.0 inches (305 mm) aft of the rear bumper face. To give the driver enough information to be able to discern if an "object," such as a child, is present and to provide a quantitative basis for assessing that the desired field of view can be seen, it is important to indicate how much of each test object must be visible. Seeing a child's face or another body area of similar size would likely result in successful visual recognition of the child by the driver. The average breadth of an 18-month-old child's head is stated to be 5.9 inches (150 mm).[37] Based on this, the criterion was developed that the full width of the 5.9-inch (150 mm) vertical stripe should be visible at some point along the height of both F and G. It was assumed that this criterion would result in an approximately 5.9-inch (150 mm) square portion of an object or child being visible. Therefore no vertical extent of the visible portion of the stripe was assessed.

In summary, for a rearview image to meet the current test procedure's criteria, two conditions must be met: First, the front surfaces of Cylinders A, B, C, D and E have to be fully visible in the display (the entire height and width of each cylinder). In addition, the full width of the 5.9 inch-wide (150 mm) vertical stripe on Cylinders F and G must be visible at some point along the height of the cylinder. If both conditions are met, then the system meets the field of view criteria established here. Figure 7 shows an image of a rearview image that meets these criteria, where Cylinders A through E are the ones furthest away in the image and Cylinders F and G have a substantial portion of their vertical stripes showing in the front corners.

To determine whether a rearview image's field of view meets the specified criteria, the displayed image was photographed to document the test results of this field of view test, as well as to provide data for use in completing the rearview image quality test, as is described in the next section.

3.4 Rearview Image Quality Test Procedure

Standardized industry standards for the assessment of the quality of a visual image of the area behind a vehicle do not currently exist. Therefore, to develop a method for assessing image quality, as previously mentioned, prior work relating to school bus cross-view mirrors was examined. The test procedure described below follows the same basic concept as the existing school bus mirror test procedure in FMVSS No. 111. This test procedure serves to ensure that a minimum image quality is maintained throughout the specified field of view of the rearview image. Essentially, meeting the image quality criteria requires that the apparent sizes of the images of the individual test objects are large enough for an average driver to quickly determine their presence and nature.

[37] The 5.9 in (150 mm) dimension is the average breadth of an 18-month-old child's head per Center for Disease Control's "Clinical Growth Charts, Birth to 36 months: Boys; Length-for-age and Weight-for-age percentiles" and "Clinical Growth Charts, Birth to 36 months: Girls; Length-for-age and Weight-for-age percentiles," published May 30, 2000 (modified 4/20/2001).

The test procedure for use in assessing countermeasure visual display image quality required one additional step beyond the rearview image viewable area test described above. Using the printed photograph of the rearview image taken to document the viewable area covered by the system, the sizes of each of the three test objects positioned 20.0 feet aft of the rear bumper (Cylinders A, B, and C in Figure 3) were measured. The horizontal width of each of the three test objects was measured within the colored band surrounding the upper portion of the cylindrical test object by selecting a point at both the left and right edges of the object's displayed image. Similarly, two points on the ruler shown in the photograph were selected to acquire a measurement for use as a lateral scaling factor. Using the two measured widths and the distance between the driver's eyepoint (i.e., midpoint between an average 50^{th} percentile male's eyes) and the center of the rearview image, the visual angle subtended by each test object was calculated. To reduce the effects of measurement errors, the measured visual angle subtended from each of the three test objects (Cylinders A, B, and C) were averaged together. Acceptable image quality was defined as the average measured visual angle subtended by the test object's width from these three locations exceeding 5 minutes of arc. The average value was used to minimize the effect of individual measurement error. The subtended visual angle for each of the three individual cylinders must exceed 3 minutes of arc.

In order to evaluate the quality of the rearview image, the photo taken from the perspective of a 50^{th} percentile adult male was analyzed to determine the size of the displayed visible area and the visual angle subtended by the object.

3.4.1 Photographic Data Extraction

In addition to the field of view test, the apparent widths of Cylinders A, B, and C were measured for calculating their subtended visual angle in the photograph. A 2.0 inch delineated section of the ruler affixed to the base of the rearview image was also measured, to provide a scale factor (*s*) for converting measurements from pixels on a computer monitor to inches. In addition to the photographic image measurements, the viewing distance (*d*) from the camera lens to the center of the rearview image was previously determined (see Section 3.2) to provide the third component needed for calculating the subtended visual angle of a test object in the displayed image.

Any photo editing software which provides zoom and pan functions, rotations, and a high resolution XY coordinate system may be used to measure the apparent size of the cylinders. For the tests described in this report, Corel Paint Shop Pro Photo X2 was used.

The photographic data extraction process is as follows:

- In-vehicle rearview video system display screens are commonly located so they do not directly face the driver but are offset from the driver's direct forward line of sight. The human eye can compensate for this and interpret the image as "normal", whereas a camera lens tends to make images appear a bit skewed and not quite horizontal when the image is offset, as shown in Figure 9. For this reason a working copy of each digital photo was first rotated to make it appear approximately horizontal. It is important to ensure that any modifications to the digital photos (including rotations) do not distort the relative distances between points in the image.

Figure 9. Example of Photographic Image, Before and After Image Rotation.

- The next step in the measurement process was to identify the points to be measured on each of the three cylinders A, B, and C and also on a 2-inch section of the ruler. For reference and to permit data quality checking, arrows were inserted in the copied photo to mark the points to be measured, as illustrated in the close-up view in Figure 10. In this testing, measurements of cylinder width were made at the lower edge of the horizontal band (highlighted in Figure 10 using arrows to ensure a horizontal measurement of width was obtained.

- After the desired reference points were marked in the image by arrows, the software "zoom" function was used to determine the coordinates of each arrow tip. The XY coordinates in pixels of each arrow tip were determined from the graphics software and entered into a spreadsheet. The 2- inch section of the ruler was measured from the tip of one inch line to the tip of another inch line 2.0 inches away to obtain a consistent method for obtaining a scaling factor.

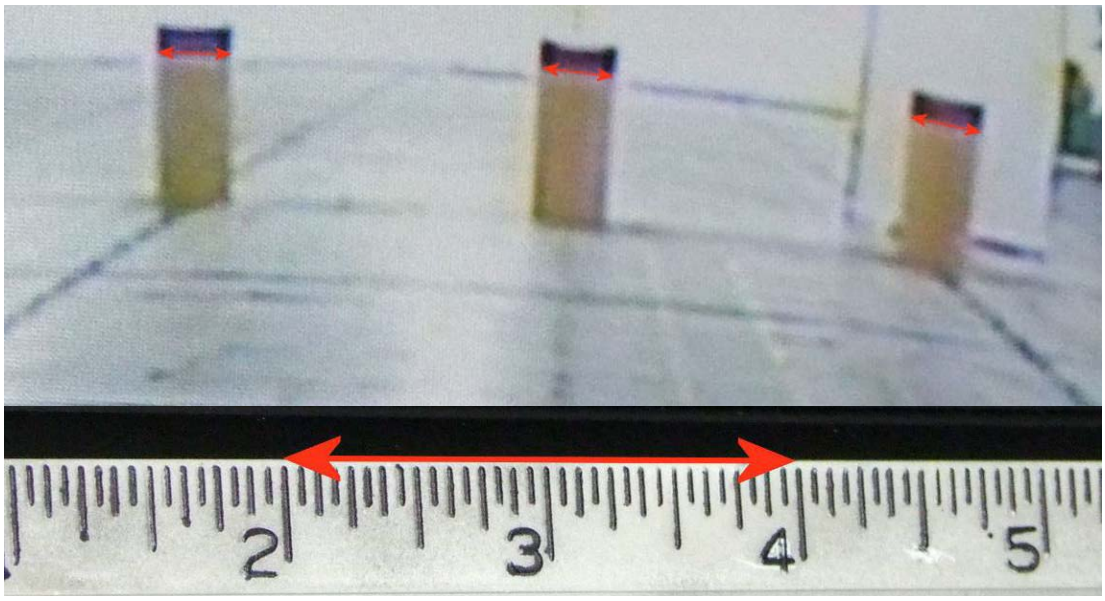

Figure 10. Close-Up View Portions of Display with Measurement Points Indicated.

3.4.2 Calculations for the Determination of Test Cylinder Subtended Visual Angle

Appendix 2 contains a derivation of the equation used to calculate the subtended visual angle of each test object. A spreadsheet was set up with formulas attached to the appropriate cells to calculate the width and visual angle of each object as the pixel coordinates were entered. This allowed for instant data quality checks.

Using the pixel coordinates obtained for each edge of each cylinder and the 2.0 inch section of the ruler, along with the previously determined viewing distance (d), the scale factor (s), apparent width in pixels (c_i), and the subtended visual angle (Θ_i) of each cylinder were calculated.

The scale factor (***s***) for the ruler in pixels per inch was found by dividing the distance between two points on the ruler in pixels by the actual distance in inches between the same two points:

$$\mathbf{s = SQRT((X_2 - X_1)^2 + (Y_2 - Y_1)^2) / 2}$$

where **(X1, Y1)** and **(X2, Y2)** are the coordinates in pixels of the endpoints of the 2.0 inch segment of the ruler used to establish the scale.

Then, if the endpoints of the arrow spanning the width of Cylinder ***i*** are $\mathbf{(X_{i1}, Y_{i1})}$ **and** $\mathbf{(X_{i2}, Y_{i2})}$, the apparent width of each cylinder in pixels is given by

$$\mathbf{c_i = SQRT((X_{i2} - X_{i1})^2 + (Y_{i2} - Y_{i1})^2)}$$

Once the width of a cylinder had been calculated in pixels, the subtended visual angle was calculated using the following formula:

$$\Theta_i = \sin^{-1}(c_i / (d * s))$$

The angular widths of the cylinders were reported in minutes of arc for each vehicle's rearview image. Visual angle results were interpreted using the previously discussed human visual performance criteria to determine whether or not an object in the view of a rearview image subtends a large enough visual angle to be detectable by a driver seated at the 50th-percentile adult male location.

4.0 APPLICATION OF THE TEST PROCEDURE AND RELATED RESULTS

The test procedures described in this report were applied to several late model vehicles to demonstrate how to carry out the measurements and how some current vehicles fare with respect to the criteria asserted in this report.

4.1 Test Vehicles Measured

Six model year 2010-2011 test vehicles were acquired for measurement. The vehicles measured were ones that happened to be on site for other research programs and were equipped with an original equipment rearview video system. Table 1 lists the model information for these vehicles.

Table 1. Vehicles Tested for the Current Study

Year	Make	Model	Vehicle Identification Number
2010	Dodge	Grand Caravan SE	2D4-RN4DE9AR-11****
2010	Ford	F-150 (super crew)	1FTFW1EU1AFB2****
2010	Nissan	Maxima	1N4AA5AP6AC82****
2010	Nissan	Murano	JN8AZ1MW7AW118****
2011	Toyota	Camry	4T4BF3EK2BR09****
2011	Toyota	Sienna	5TDYK3DC8BS01****

Table 2 shows the information recorded during the measurement fixture configuration process for each vehicle. Head/neck rotation angle is the amount of rotation from a directly forward line of sight the fixture was rotated to allow the camera's line of sight to align with the lateral location of the rearview image. 'Pitch Angle' in Table 2 refers to the amount of pitch about a horizontal axis containing M_r the camera was rotated in order for the camera's line of sight to intersect with the center of the rearview image. The viewing distance (*d*) from the rotated eye point (M_r) to the center of the rearview image was measured for use in calculating subtended visual angle of the test cylinders. Number of occupied seats refers to the number of occupant locations in which weights were location to simulate the weight of vehicle passengers.

Table 2. Image Quality Measurement Data and Fixture Positioning Information by Vehicle

Vehicle Year/Make	**Vehicle Model**	**Rearview Image Diagonal Length** (in)	**Rearview Image Location**	**Head/Neck Rotation Angle**	**Pitch Angle** (Camera rotated about a horizontal line containing M_r)	**Number of 'Occupied' Seats** (other than driver's)	***d*** (in)
2010 Dodge	Caravan	7.25	Center Stack	35°	-17.9	3	29.34
2010 Ford	F-150	2.40	Interior Mirror	35°	--	0	27.20
2010 Nissan	Maxima	7.25	Center Stack	25°	-13.2	4	32.48
2010 Nissan	Murano	7.80	Center Stack	30°	-15.8	4	33.98
2011 Toyota	Camry	7.25	Center Stack	27°	-24.0	4	30.34
2011 Toyota	Sienna	7.25	Center Stack	33°	-18.0	4	32.60

* Pitch Angle was unavailable for the 2010 Ford F-150.

4.2 Rearview Image Field of View Assessment

Figures 11 through 16 show photographs of each test vehicle's rearview video system display. These photographs were used to determine whether each rearview image met the field of view specified in Section 2.2 and Section 3.3 as well as the image quality requirements described in

Section 3.4. As can be determined from an examination of these figures, all six test vehicles rearview video systems met the field of view requirements described in Section 2.2.

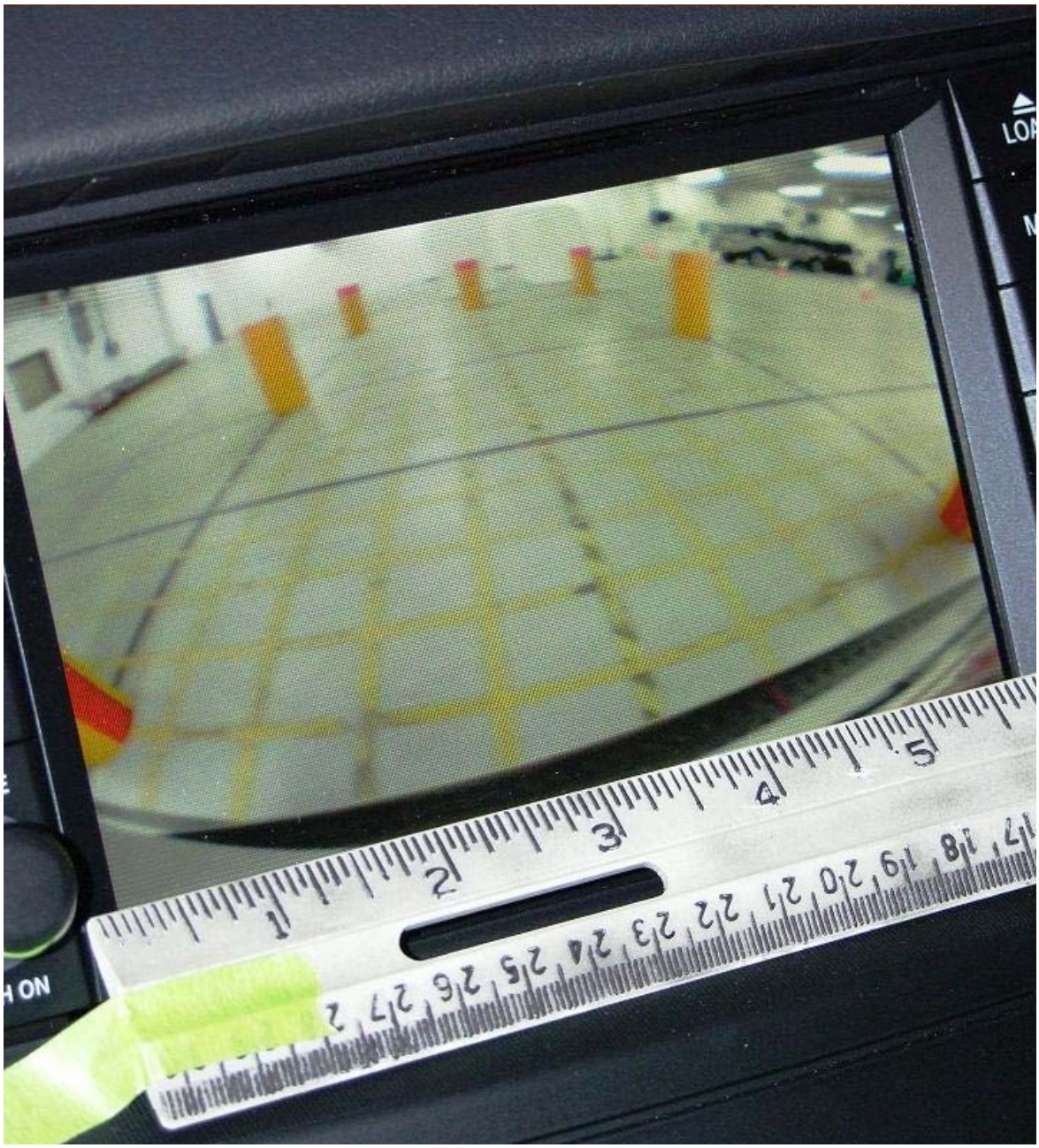

Figure 11. Field of View and Image Quality Assessment Photo for the 2010 Dodge Grand Caravan

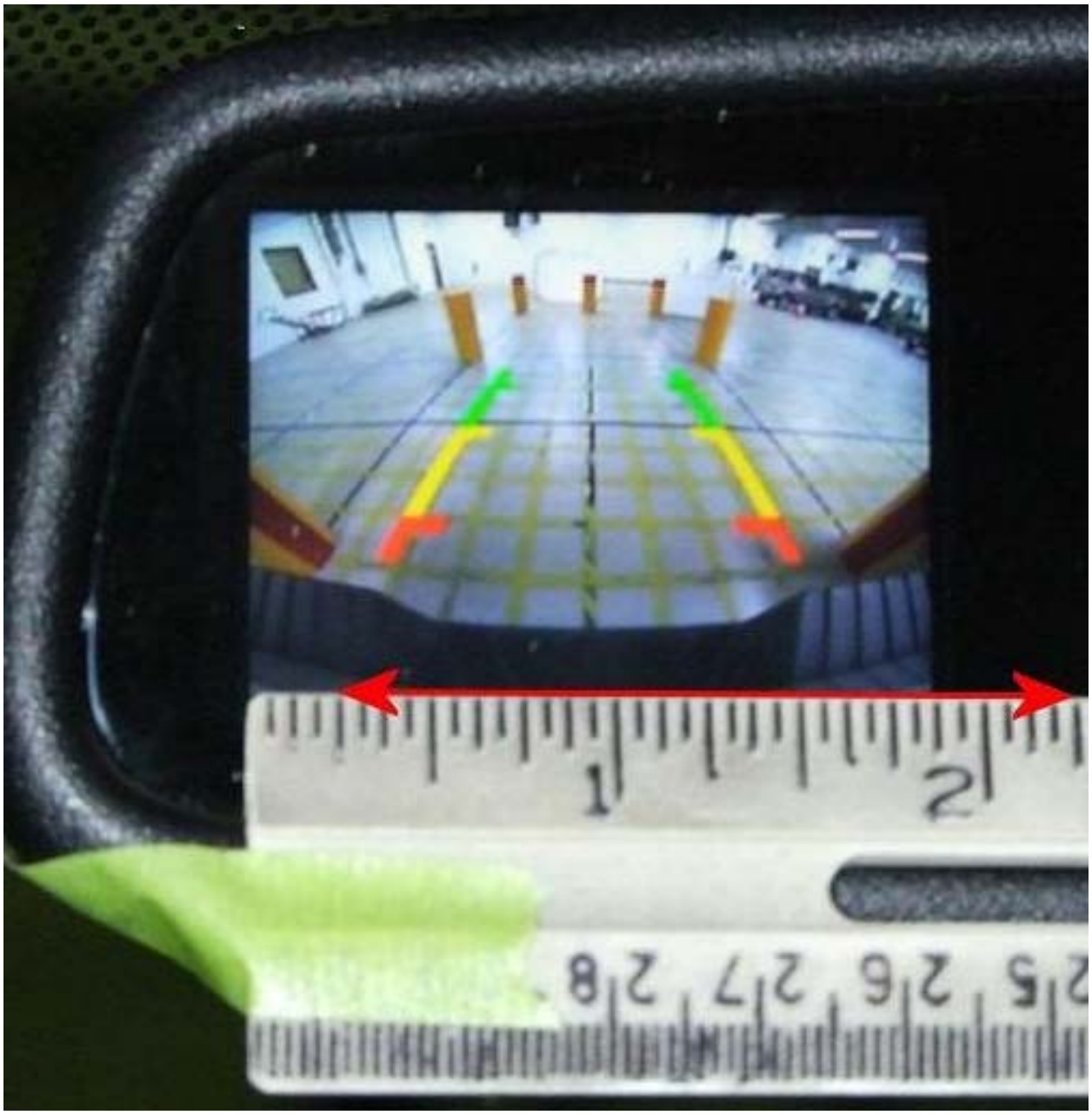

Figure 12. Field of View and Image Quality Assessment Photo for the 2010 Ford F150

Figure 13. Field of View and Image Quality Assessment Photo for the 2010 Nissan Maxima

Figure 14. Field of View and Image Quality Assessment Photo for the 2010 Nissan Murano

Figure 15. Field of View and Image Quality Assessment Photo for the 2011 Toyota Camry

Figure 16. Field of View and Image Quality Assessment Photo for the 2011 Toyota Sienna

4.3 Rearview Image Quality Assessment

Measured image quality data for the six vehicles determined Figures 10 through 15 and is summarized in Table 3. This table shows the image scale calculations, the x and y pixel coordinates of Cylinders A, B, and C, and the apparent width and visual angle calculations for each of these cylinders.

The 2010 Ford F-150 had the smallest subtended visual angles for Cylinders A, B, and C (an average of 4.12 minutes for the three) and the 2010 Dodge Grand Caravan had the largest subtended visual angle (an average of 14.84 minutes for the three). The 2010 Ford F-150 subtended visual angles were small, compared to the other five test vehicles, because it was the only one of the six vehicle to have a 2.4-inch diagonal video display in its interior rearview

mirror. The other five test vehicles, all of which had 7- to 8-inch diagonal video displays in their center consoles, all had approximately equal subtended visual angles.

Section 2.3 lists the two image quality criteria used in this research. They were:

1. When the apparent angular size of the three test cylinders that are located 20.0 feet aft of the rearmost point on the vehicle's rear bumper (Cylinders A, B, and C in Figure 6) are measured, the average apparent angular size of the three must not be less than 5 minutes of arc when viewed in the rearview image.
2. When viewed in the rearview image, the apparent angular size of each individual test cylinder must not be less than 3 minutes of arc.

As can be seen by inspection of Table 3, the 2010 Ford F-150 does not meet the first of these requirements. As discussed above, this is due to the size of its video display. If this vehicle were equipped with a 3.0 inch or larger diagonal display, it would have met the first criterion. This vehicle did meet the second criterion with its current display.

Even though the 2010 Ford F-150 the rearview video system display installed in this vehicle is not large enough to meet the image quality requirements contained in this report, this display should certainly improve safety relative to not having a display.

The rearview video systems of the other five test vehicles would meet both of the above listed image quality criteria.

Table 3. Image Quality Measurements: Apparent Linear Width and Visual Angle Calculations for Cylinders A, B, and C Positioned 20.0 Feet Behind the Vehicle's Rear Bumper

Vehicle	d (in)	Ruler Measurements (2 inches)				s	Cylinder A Measurements				c_a Width		Θ_a Visual Angle
		x1	y1	x2	y2	Pixels/ Inch	x1	y1	x2	y2	Pixels	In.	Min.
2010 Dodge Grand Caravan	29.34	351	2278	1305	2298	477.1	1400	865	1455	874	55.7	0.117	13.7
2010 Ford F-150	27.20	926	2378	2298	2390	686.0	1513	1613	1535	1614	22.0	0.032	4.1
2010 Nissan Murano	33.98	1250	2786	2174	2802	462.1	2035	1432	2094	1438	59.3	0.128	13.0
2010 Nissan Maxima	32.48	1363	2703	2270	2716	453.5	1968	1469	2029	1471	61.0	0.135	14.2
2011 Toyota Camry	30.34	1982	3022	2822	3022	420.0	2198	1687	2252	1688	54.0	0.129	14.6
2011 Toyota Sienna	32.60	1449	3059	2307	3069	429.0	2052	1564	2111	1566	59.0	0.138	14.5
Vehicle	**d (in)**	**Ruler Measurements (2 inches)**				**s**	**Cylinder B Measurements**				**c_b Width**		**Θ_b Visual Angle**
		x1	y1	x2	y2	Pixels/ Inch	x1	y1	x2	y2	Pixels	In.	Min.
2010 Dodge Grand Caravan	29.34	351	2278	1305	2298	477.1	1078	812	1141	819	63.4	0.133	15.6
2010 Ford F-150	27.20	926	2378	2298	2390	686.0	1385	1606	1408	1606	23.0	0.034	4.2
2010 Nissan Murano	33.98	1250	2786	2174	2802	462.1	1705	1397	1769	1401	64.1	0.139	14.0
2010 Nissan Maxima	32.48	1363	2703	2270	2716	453.5	1653	1445	1715	1447	62.0	0.137	14.5
2011 Toyota Camry	30.34	1982	3022	2822	3022	420.0	1948	1660	1997	1662	49.0	0.117	13.2
2011 Toyota Sienna	32.60	1449	3059	2307	3069	429.0	1769	1526	1827	1527	58.0	0.135	14.3
Vehicle	**d (in)**	**Ruler Measurements (2 inches)**				**s**	**Cylinder C Measurements**				**c_c Width**		**Θ_c Visual Angle**
		x1	y1	x2	y2	Pixels/ Inch	x1	y1	x2	y2	Pixels	In.	Min.
2010 Dodge Grand Caravan	29.34	351	2278	1305	2298	477.1	743	795	805	799	62.1	0.130	15.3
2010 Ford F-150	27.20	926	2378	2298	2390	686.0	1253	1608	1275	1608	22.0	0.032	4.1
2010 Nissan Murano	33.98	1250	2786	2174	2802	462.1	1373	1395	1431	1395	58.0	0.126	12.7
2010 Nissan Maxima	32.48	1363	2703	2270	2716	453.5	1334	1448	1393	1449	59.0	0.130	13.8
2011 Toyota Camry	30.34	1982	3022	2822	3022	420.0	1682	1642	1732	1642	50.0	0.119	13.5
2011 Toyota Sienna	32.60	1449	3059	2307	3069	429.0	1467	1518	1527	1518	60.0	0.140	14.7

5.0 SUMMARY

In support of the mandate to improve vehicle rear visibility outlined in the Kids Transportation Safety Act of 2007, NHTSA investigated the nature of backover crashes and looked into what information may be effective in aiding drivers to avoid backover crashes. Crash data were examined to better understand the backover problem and the locations in which victims tend to be located with respect to the backing vehicle in documented incidents. NHTSA also examined technologies that may aid the driver in detecting rear obstacles and pedestrians. This report describes the process used to determine what field of view behind a vehicle (i.e., their field of view) affords a driver the best chance of preventing a backover crash. The degree of the image quality needed for a driver to effectively discern relevant obstacles within this field of view was also determined. The development of test procedures for measuring both the field of view and image quality of rearview images was described. Finally, the use of the developed test procedures was demonstrated through the measurement of the field of view and image quality of rearview images associated with six 2010-2011 model year vehicles equipped with original equipment rearview video systems.

NHTSA's research to date has shown that systems providing the driver with an image of the area behind the vehicle are more effective in aiding a driver to avoid a backing crash with a rear obstacle than other types of technologies. However, for drivers to see and identify objects displayed within a rearview image, the image must have an adequate field of view and sufficient image quality to permit the average driver to see what is in the field of view.

A procedure was developed for use in assessing a rearview image's ability to meet the specified field of view. The field of view specified consisted of a 10.0 feet wide by 20.0 feet long area and was delineated using seven test objects. Each test object was a cylinder of 12.0 inches (305 mm) in diameter and 32.00 inches (813 mm) in height. For the purposes of this work, criteria for visibility of the test objects were asserted to ensure that the field of view would be useful to drivers in discerning child-sized objects behind a vehicle. For test objects located 10.0 feet (3.05 meters) or more aft of the vehicle's rear bumper, the entire height and width of each test object should be visible. This criterion equates to the driver being able to see the entire body of an 18-month-old child, if present, between 10.0 feet (3.05 meters) and 15.0 feet (4.57 meters) behind the vehicle. Due to camera angle, only a portion of a child or child-sized object in close proximity to the rear bumper may be visible, particularly at the edges of the camera's viewing angle. To ensure that at least a portion of Cylinders F and G were visible; the test procedure used here positioned these cylinders 12.0 inches (305 mm) aft of the rear bumper face. To give the driver enough information to be able to discern if an "object," such as a child, is present and to provide a quantitative basis for assessing that the desired field of view can be seen, it is important to indicate how much of each test object must be visible. Seeing a child's face or another body area of similar size would likely result in successful visual recognition of the child by the driver. The average breadth of an 18-month-old child's head is stated to be 5.9 inches (150 mm).[38] Based on this, the measurement procedure used here assessed whether the full 5.9-

[38] The 5.9 in (150 mm) dimension is the average breadth of an 18-month-old child's head per Center for Disease Control's "Clinical Growth Charts, Birth to 36 months: Boys; Length-for-age and Weight-for-age percentiles" and "Clinical Growth Charts, Birth to 36 months: Girls; Length-for-age and Weight-for-age percentiles," published May 30, 2000 (modified 4/20/2001).

inch (150 mm) width of the vertical stripe was visible at some point along the height of both F and G.

In summary, for a rearview image to meet this effort's test procedure requirements, two conditions needed to be met: First, the front surfaces of Cylinders A, B, C, D and E have to be fully visible in the system's display (the entire height and width of each cylinder). In addition, the full width of the 5.9- inch (150 mm) wide vertical stripe on Cylinders F and G must be visible at some point along the height of the cylinder. If both conditions were met, then the system is considered to have met the field of view criteria outlined here.

Image quality measurements assess whether a rearview image will enable the driver to see and identify objects behind the vehicle's rear bumper. For this effort, the apparent angular size of a test object having known actual size and location was calculated using (1) the distance between the display screen and a camera, mounted so as to represent the view observable by a 50^{th}-percentile height male driver and (2) the test object's linear dimensions as seen in a photograph of the rearview image. Details of the calculation procedure were provided in the main body of the report. Image quality criteria based on the apparent test object angular size were then applied to determine whether drivers will be able to see each test object. (Image quality also includes image distortion; however, distortion was not measured here because it is not an issue for the technologies assessed in this effort; i.e., rearview video systems.) The following criteria were used in this evaluation:

1. When the apparent angular size of the three test cylinders that are located 20.0 feet aft of the rearmost point on the vehicle's rear bumper (Cylinders A, B, and C) are measured, the average apparent angular size of the three must not be less than 5 minutes of arc when viewed in the rearview image.
2. When viewed in the rearview image, the apparent angular size of each individual test cylinder must not be less than 3 minutes of arc.

There is no need for criteria based on the apparent angular size requirements for any of the nearer test objects, since with the types of technologies anticipated for this application, the three furthest test objects will always appear to be the smallest, thus representing the worst case for visibility among the seven cylinders.

Field of view and image quality measurements outlined in this report were evaluated for six model year 2010-2011 test vehicles equipped with original equipment rearview video systems. These rearview video systems use a video camera and visual display to provide the driver with an image of the area behind the vehicle. While other rearview imaging technologies, such as mirrors or fiber optics, could also be used to provide the driver with an image of the area behind the vehicle, no original equipment of this type was known to be available in any current production vehicle. However, should other imaging technologies come to be used, the test procedures described in this report could also be applied to these technologies.

All six test vehicles rearview video systems met the field of view requirements outlined in this report. Based on the performance of original equipment systems examined by NHTSA, the field of view proposed in the NPRM should be obtainable through the installation of a single video camera with a minimum horizontal viewing angle of 130 degrees located at or near the centerline of the vehicle.

With regard to image quality measurements performed, the 2010 Ford F-150 had the smallest subtended visual angles for Cylinders A, B, and C (an average of 4.12 minutes for the three) and the 2010 Dodge Grand Caravan had the largest subtended visual angle (average of 14.84 minutes for the three). The 2010 Ford F-150 subtended visual angles were small, compared to the other five test vehicles, because it was the only one of the six vehicle to have a 2.4-inch diagonal video display in its center rearview mirror. The other five test vehicles, all of which had 7- to 8-inch diagonal video displays in their center consoles, all had approximately equal subtended visual angles.

The 2010 Ford F-150 did not meet the first of the two image quality requirements listed above due to the small size of its video display. If this vehicle were equipped with a 3.0-inch or larger diagonal display, it would have likely met the first criterion. This vehicle did meet the second criterion with its current display. Even though the 2010 Ford F-150 the rearview video system display installed in this vehicle was not large enough to meet the image quality requirements proposed in the NPRM.

The rearview video systems of the other five test vehicles would meet both of the above image quality criteria.

APPENDIX 1. DEVELOPMENT OF A REARVIEW IMAGE QUALITY MEASUREMENT FIXTURE

Objective

To perform consistent and repeatable image quality measurements of objects visible in vehicle rearview video displays, a fixture was developed to hold a camera at a test reference point representing a location between the eyes of a 50th-percentile adult male driver looking at a rearview video display inside the vehicle. With a camera in this position, photographs can be taken that represent the view observable by a fiftieth percentile adult male driver. By extracting measurements from such photographs, the quality of an image provided by a rearview video system can be assessed.

Fixture Design

To facilitate a repeatable test procedure, an H-Point machine representing the 50th- percentile adult male was used as the base for the fixture. The H-Point machine was selected as the base to provide a standardized representation of the seated posture of an adult male driver. The H-point machine's standard configuration was modified to incorporate a fixture mounted in place of the device's neck, as seen in Figure 17. The fixture has multiple points of adjustment such that it can be adjusted to hold the camera in a specific position that corresponds to the selected eye midpoint of a 50th-percentile adult male driver.

Figure 17. Camera & Mounting Fixture on Neck of H-Point Machine

The location of the forward-looking eye midpoint (M_f) was calculated using the measurements described in the NHTSA Technical Report "*Direct Rear Visibility of Passenger Cars: Laser-Based Measurement Development and Findings for Late Model Vehicles*"[39]. Calculations based on the previous findings determined that the M_f point would need to be located 24.88 inches (632mm) vertically and -3.80 inches (-96mm) longitudinally (i.e., rearward) with respect to the H-Point machine, as shown in Figure 4 (Note: the coordinates shown in Figure 4 are also presented in Figure 23 on the actual camera mount fixture drawings.)

In addition to the forward-looking eye midpoint (M_f), the fixture also needed to have points of head and neck rotation similar to a 50th percentile adult male. The fixture was designed to rotate about the head/neck joint center (J) in a horizontal plane. To accomplish this rotational capability, a panoramic head (a camera mount typically used for taking panoramic photos) was mounted to the centerline of the neck. This provided the rotation with the ability to lock the fixture into a desired location. The panoramic head included graduated markings to provide a record of the rotation angle used, as shown in Figure 18.

Figure 18. Neck of Fixture, a Panoramic Head

To allow for fine adjustment and future versatility, two quick release adapters with sliding plates and a rotation index guide (from a Manfrotto Virtual Reality SPH/Cubic Head) were used in conjunction with a mounting plate made of a section of angled aluminum. While in the forward-looking position, the first quick release adapter, sliding plate and section of aluminum allowed for making fine longitudinal adjustments. The horizontal portion of the section of aluminum provided a 2.91 inch lateral offset to center the camera lens with the center of the body line. The vertical portion of the section of aluminum produces the majority of the longitudinal offset to position the CCD of the specific camera used at the approximate M_f point. The vertical portion of the section of aluminum also has a rotation index guide mounted to the second quick release adapter and sliding plate combination. These parts mount the camera to the section of aluminum and allow the CCD to pitch about a horizontal axis containing the point M_r (rotated M_f) to

[39] Mazzae, E. N. and Barickman, F., *Direct Rear Visibility of Passenger Cars: Laser-Based Measurement Development and Findings for Late Model Vehicles*, U.S. Department of Transportation, National Highway Traffic Safety Administration, DOT HS 811 174, March 2009.

simulate the eye looking up or down, as needed, to shift the line of sight to intersect with the center of the rearview image. No head pitch was simulated as it was assumed to be unlikely or negligible.

A close-up image of the camera mounting system (adapters, sliding plates, rotation index guide, section of aluminum and panoramic head) is presented in Figure 19. Engineering drawings of the fixture design can be found in Figures 20 through 25.

Figure 19. Camera Mounting System.

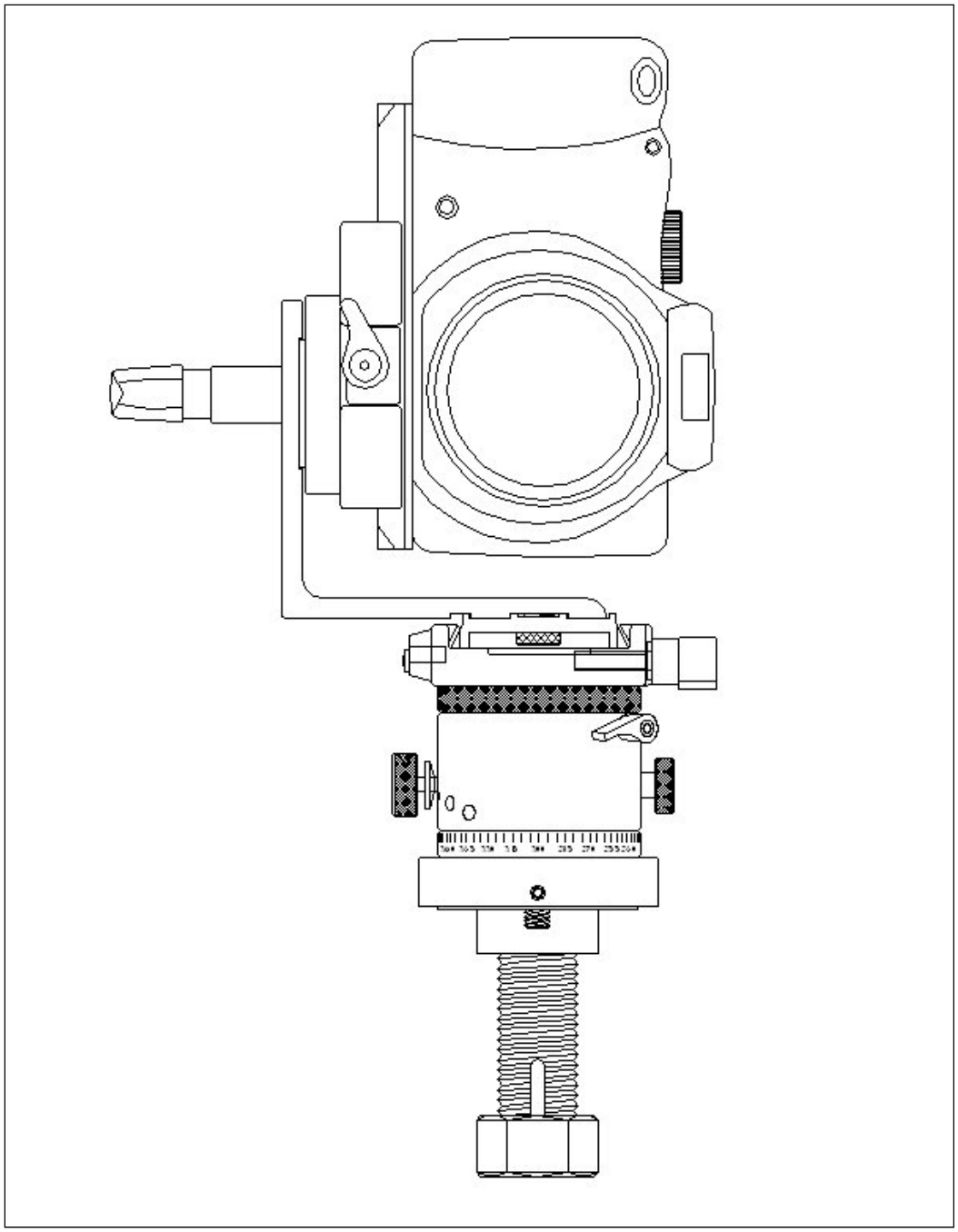

Figure 20. Front View of Camera and Mount

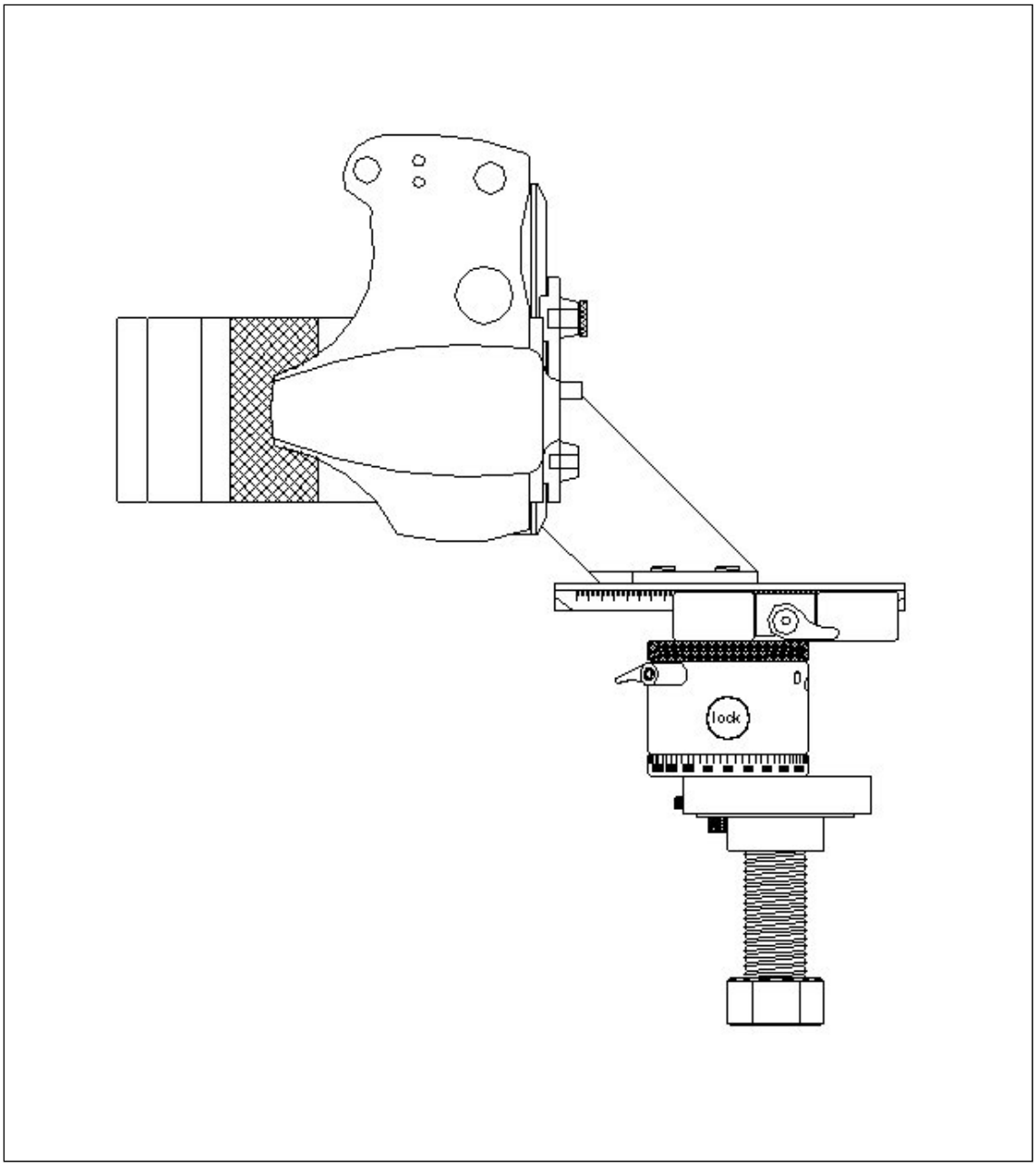

Figure 21. Right Side View of Camera and Mount

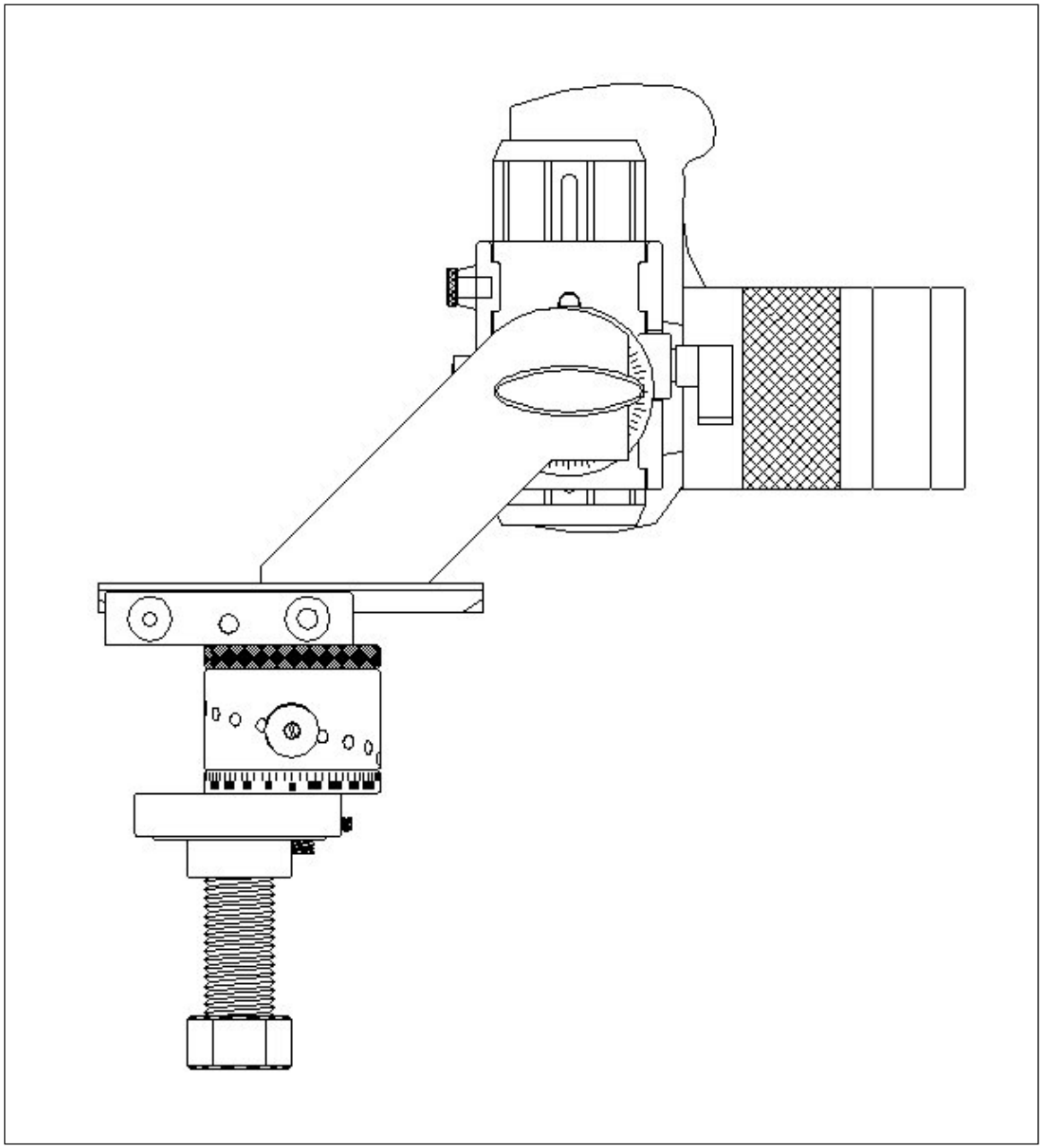

Figure 22. Left Side View of Camera and Mount

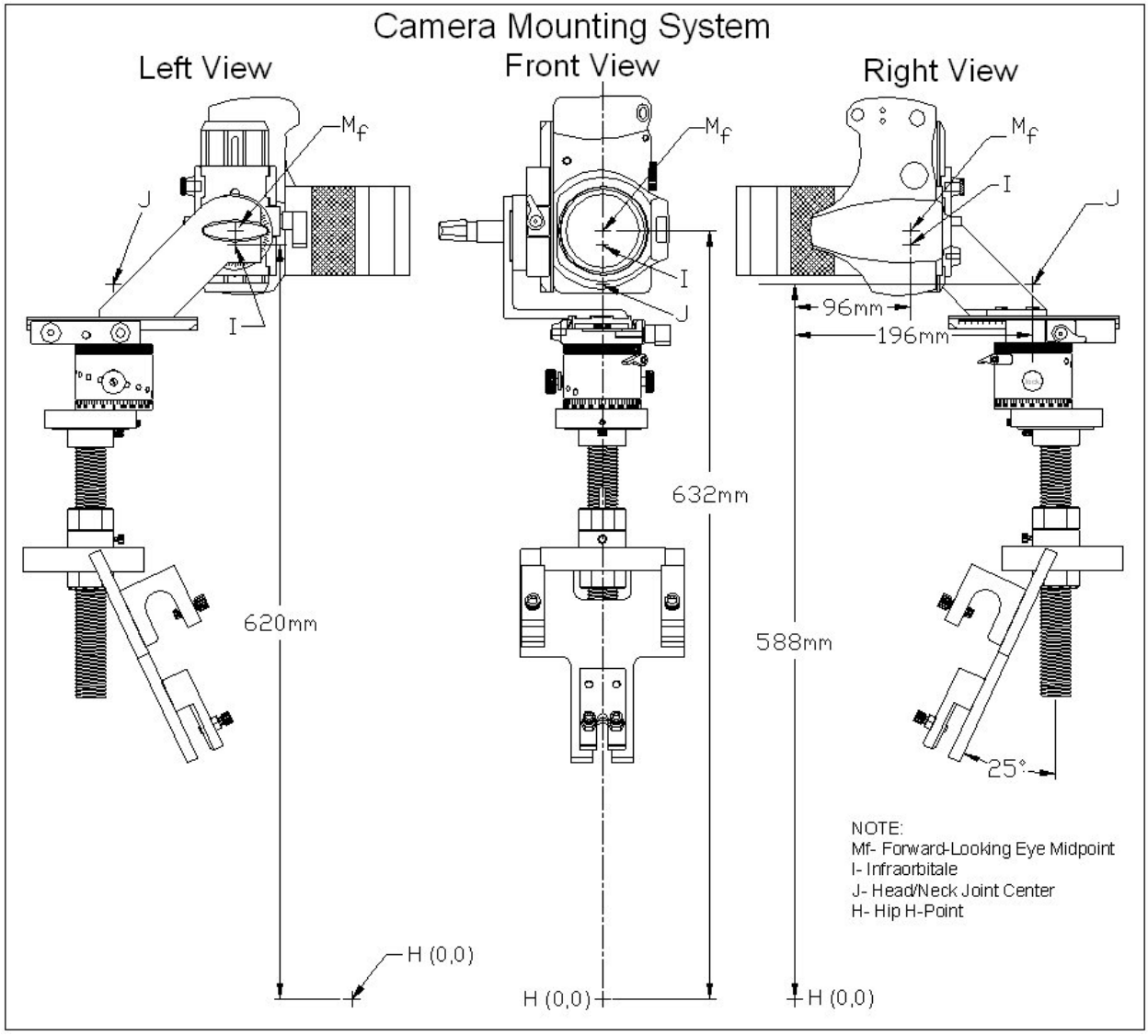

Figure 23. Camera Mounting System, Three Views, with Coordinates (M_f, I, J, H)

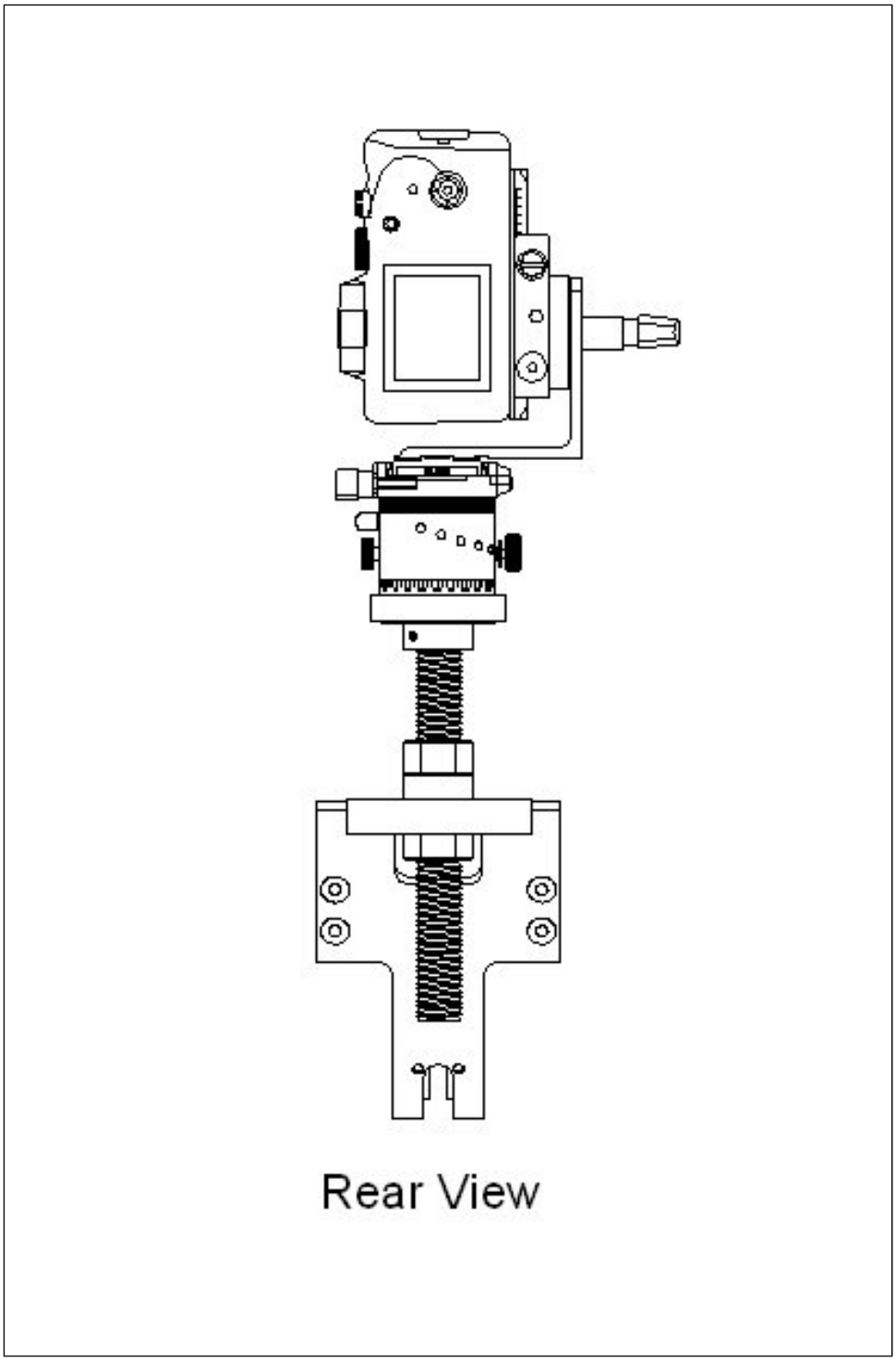

Figure 24. Back View of Camera and Mount

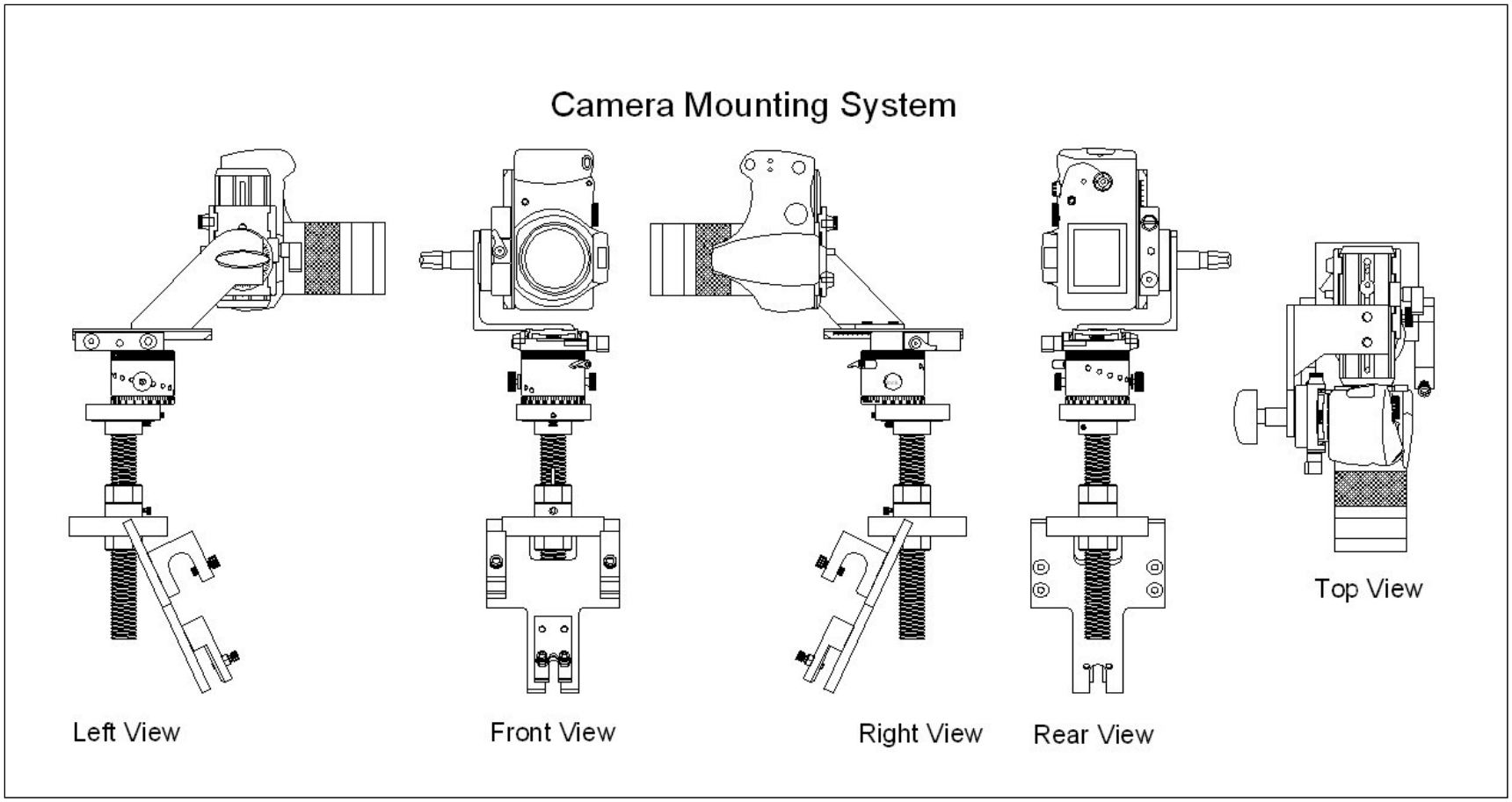

Figure 25. Camera Mounting System, All Five Views

Below are views of the image quality camera fixture as installed in two of the test vehicles.

Figure 26. Photos of the Image Quality Assessment Camera Fixture Installed in Test Vehicles

Top: 2010 Ford F-150, Side View
Bottom: 2010 Nissan Maxima, Side View (Left), Front View (Right)

APPENDIX 2. A DERIVATION OF THE EQUATION USED TO CALCULATE THE SUBTENDED VISUAL ANGLE OF EACH TEST OBJECT

Assumption 1: The plane upon which the image is displayed (may be a mirror, a video display, or some other surface) is, at least locally, flat. (This works, even for convex mirrors, because the image being analyzed is small compared to the radius of curvature of the mirror, video display, or other surface.)

Assumption 2: The plane upon which the image is displayed (may be a mirror, a video display, or some other surface) is perpendicular to the driver's line of sight at some point. While this is not in general exactly true, the difference from perpendicularity has been typically small in systems that NHTSA has tested to date.

Figure 27 shows the geometry of the situation and defines the symbols used.

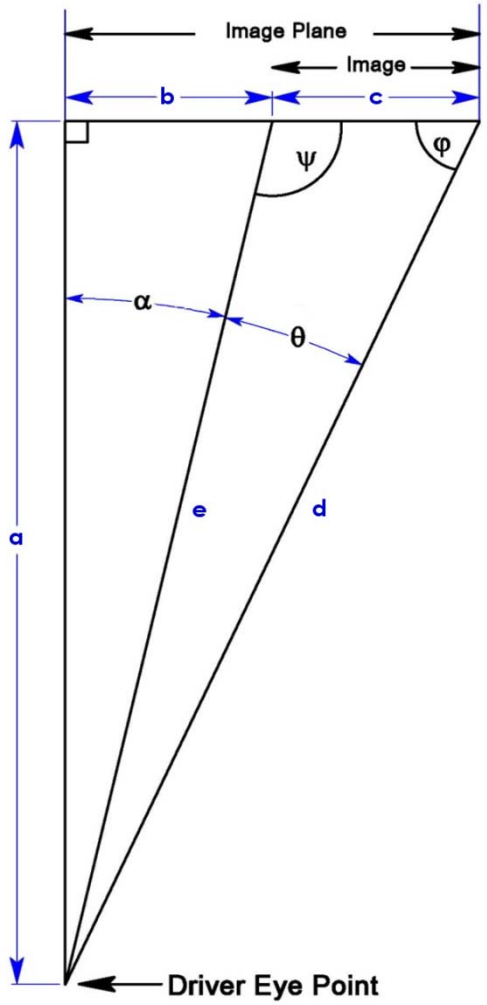

Figure 27. Geometry Used to Derived Subtended Visual Angle Equation

Definitions:
In the figure, c is the width of the actual image in the Image Plane, a is the perpendicular distance from the Driver's Eyepoint to the Image Plane, and Greek letters denote angles. The subtended visual angle that is to be determined is denoted by θ.

Case 1: One Edge of Image at Perpendicular Point

This is a special case in which one edge the image is at the point in the Image Plane that is intersected by the perpendicular line emanating from the Driver's Eyepoint. In the figure, this corresponds to the angle, α, and the distance, b, being zero. For this case, using the standard trigonometric definition of tangent,

$$\tan\theta = \frac{c}{a} \qquad (1)$$

Equation (1) can be rearranged to:

$$\theta = \tan^{-1}\frac{c}{a} \qquad (2)$$

Case 2: One Edge of Image Not at Perpendicular Point

This is a more general case in which an edge the image is no longer assumed to be at the point in the Image Plane that is intersected by the perpendicular line emanating from the Driver's Eyepoint. Then, from the Law of Sines, the following equation is true:

$$\frac{\sin\theta}{c} = \frac{\sin\Psi}{d} = \frac{\sin\varphi}{e} \qquad (3)$$

Where

$$e = \sqrt{b^2 + a^2} \qquad (4)$$

$$d = \sqrt{(c+b)^2 + a^2} \qquad (5)$$

$$\Psi = 90° + \alpha \qquad (6)$$

$$\alpha = \tan^{-1}\frac{b}{a} \qquad (7)$$

$$\varphi = 90° - \alpha - \theta \qquad (8)$$

Using Equations (6) and (8), Equation (3) can be reduced to:

$$\frac{\sin\theta}{c} = \frac{\cos\alpha}{d} = \frac{\cos(\alpha + \theta)}{e} \qquad (9)$$

It is difficult to determine the exact point on the Image Plane that is precisely perpendicular to the line emanating from the Driver's Eyepoint. Therefore, it is practically impossible to accurately measure the distance e. To allow for an approximate solution of Equation (9), to additional assumptions will be made:

Assumption 3: The distance c is much smaller than the distance a. Therefore, the angle θ will be small (less than 1 degree for the situations being considered).

Assumption 4: The distance b is much smaller than the distance a. Therefore, the angle α will be small (less than 1 degree for the situations being considered).

Using Assumptions 3 and 4, the quantity $(b + c)$ is also much smaller than the distance d.

Assumptions 3 and 4 were used to simplify the $\cos\alpha/d$ term in Equation (9). Each part of this term was expanded in a MacLaurin series in powers of c/a and b/a and second order, or higher, terms deleted as too small to matter.

Start with simplifying Equation (5):

$$d = a\sqrt{1 + f^2} \qquad (10)$$

where

$$f = \frac{b + c}{a} \qquad (11)$$

As stated above,

$$f \ll 1 \qquad (12)$$

To expand c in a MacLaurin series, the first two derivatives of c with respect to f need to be calculated and evaluated at $f = 0$

$$\frac{dd}{df} = \frac{fa}{\sqrt{1 + f^2}} \qquad (13)$$

$$\left.\frac{dd}{df}\right|_{f=0} = 0 \qquad (14)$$

$$\frac{d^2d}{df^2} = \frac{a}{\sqrt{1 + f^2}} - \frac{f^2a}{\sqrt{(1 + f^2)^3}} \qquad (15)$$

$$\left.\frac{d^2d}{df^2}\right|_{f=0} = a \qquad (16)$$

$$d = a + \frac{a}{2} f^2 + Higher\ Order\ Terms \qquad (17)$$

Neglecting all terms of order f^2 or higher, compared to a, yields

$$d \cong a \qquad (18)$$

Next, simplify Equation (7) using the standard MacLaurin series expansion for arctangent:

$$\alpha = \tan^{-1}\frac{b}{a} = \frac{b}{a} - \frac{1}{3}\left(\frac{e}{a}\right)^3 + Higher\ Order\ Terms \qquad (19)$$

Neglecting all terms of order $\left(b/a\right)^2$ or higher yields

$$\alpha \cong \frac{b}{a} \qquad (20)$$

Using the standard MacLaurin series expansion for cosine:

$$\cos\alpha = 1 - \frac{1}{2}\left(\frac{b}{a}\right)^2 + \mathit{Higher\ Order\ Terms} \qquad (21)$$

Neglecting all terms of order $\left({}^{b}/_{a}\right)^2$ or higher yields

$$\cos\alpha \cong 1 \qquad (22)$$

The ${}^{\cos\alpha}/_{d}$ term in Equation (9) therefore can be simplified, based to the assumptions made, to ${}^{1}/_{a}$. The first two terms in Equation (9) have, therefore, been reduced to:

$$\frac{\sin\theta}{c} = \frac{1}{a} \qquad (23)$$

or

$$\theta = \sin^{-1}\frac{c}{a} \qquad (24)$$

Two equations, Equations (2) and (24), have now been developed for the subtended visual angle θ. Equation (2) is exact but only applies to the special case in which one edge the image is at the point in the Image Plane that is intersected by the perpendicular line emanating from the Driver's Eyepoint. Equation (24) applies to the more general case in which one edge the image is **not** at the point in the Image Plane that is intersected by the perpendicular line emanating from the Driver's Eyepoint, however, it relies on small angle approximations. Note that for small angles, both Equations (2) and (24) are identical since

$$\sin^{-1}\theta \cong \tan^{-1}\theta \cong \theta \qquad (25)$$

Therefore, both Equations (2) and (24) reduce, for small angles to:

$$\theta = \frac{10800}{\pi} \times \frac{c}{a} \qquad (26)$$

Where $10800 / \pi$ is the correct constant to convert ${}^{c}/_{a}$ into minutes of arc. Equation (26) provides a third equation for determining the subtended visual angle.

Each of Equations (2), (24), and (26) was used to calculate a subtended visual angle for a given ${}^{c}/_{a}$ value. The ${}^{c}/_{a}$ value used was 0.00145444053054153000. The resulting values of θ were 4.999994711511520 minutes of arc from Equation (2), 5.000000000000000 minutes of arc from Equation (24), and 4.999998237167900 minutes of arc from Equation (26).

The above calculations demonstrate two things:

1. For the angles of interest, there is a minimal difference in the subtended visual angle that was calculated with a maximum difference of 0.000005288488482 minutes of arc. This sixth decimal place difference is well beyond the accuracy of the procedures used to

measure a and d. Therefore, from an accuracy point of view, it does not matter which of these equations is used.

2. Equation (24), which utilized the arcsine function, calculated the largest value of θ. Therefore, this is the equation that helps the most when trying to fare well in an image quality assessment based on a minimum subtended visual angle.

Based on the above discussion, the preferred equation for calculating the subtended visual angle is:

$$\theta = \sin^{-1}\frac{c}{a} \qquad (24)$$

In the case where Assumption 2 is not true (the plane upon which the image is displayed is not perpendicular to the driver's line of sight, the subtended angle will be calculated based on the apparent size of the object in the plane in which the image is displayed. As the ultimate goal of measuring subtended angles is to determine how much area the reflected object occupies in the driver's field of view, the apparent size is the correct measurement. Define e as zero and the projection of α onto a plane perpendicular to the line of sight will be designated as α' (see Figure 28). In this case Equation 2 can be used:

$$\theta = \tan^{-1}\frac{c'}{a} \qquad (27)$$

Using the small angle approximation, Equation 27 becomes:

$$\theta = \sin^{-1}\frac{c'}{a} \qquad (28)$$

Which is the same as Equation 24 with α' substituting for α.

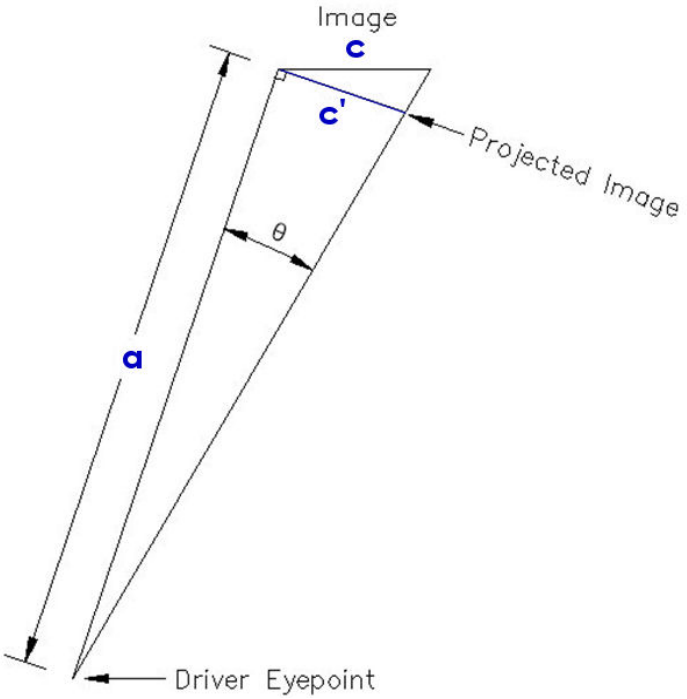

Figure 28. Calculation of Subtended Visual Angle for Case Where Plane in Which Image is Displayed is Not Perpendicular to Driver's Line of Sight

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