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16. Abstract

Mirror fields of view (FOV) of 43 men and women were measured in their own passenger cars. A manual pole-sighting method was supplemented by calculations from three-dimensional vehicle data. A coordinate measurement machine was used to record the mirror orientations and driver eye locations.

The mean horizontal FOV widths were 12.9, 25.3, and 22.5 degrees for the left (driver-side), center, and right mirrors, respectively. On average, drivers could see 14.0 degrees outboard on the left and 19.8 degrees outboard on the right. Driver age, gender, and body size did not significantly affect mirror aim. The vehicle defined the edge of the horizontal FOV in the left and right mirrors for 84 percent and 78 percent of drivers in the left and right mirrors, respectively. On average, the vehicle took up 21 percent of the available horizontal FOV in the left mirror. FOV were not significantly different after the drivers were allowed to reaim the mirrors, except that the outer edge of the left mirror horizontal FOV increased to 15.1 degrees outboard.

The distributions of mirror FOV parameters were comparable to those reported in an earlier study, but the current data are much more detailed and include the physical mirror orientation, mirror dimensions, mirror positions relative to driver eye location, and other information. Summary statistics on the parameter distributions are provided to facilitate modeling of mirror FOV.

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Contents

Introduction

Data on mirror aiming and fields of view are useful for a variety of analyses relating to indirect vision. Flannagan and Flannagan (1998) examined the requirements for driver-side mirror adjustment range, using several different potential targets. Using the SAE J941 eyellipse to represent the distribution of driver eye locations (SAE 1998), the authors presented methods for determining the horizontal and vertical ranges of angular adjustment that would be required for a desired percentage of drivers to see selected point or line targets in the rear field of view. Federal Motor Vehicle Safety Standard (FMVSS) 111 provides specific targets that must be visible in mirrors, based on an analysis from eye points determined from the eyellipse, but drivers may not choose to aim their mirrors to view those targets. Hence, the mirror field of view in actual use may be different from that specified in FMVSS 111.

There have been few previous studies of the fields of view provided by vehicle mirrors in actual use. Olson and Winkler (1985), in a study of vehicle characteristics potentially related to crash avoidance, used a pole-sighting technique to measure the fields of view of 620 drivers in their own vehicles. Cumulative distributions of the edges of fields of view in the driver-side (left), center, and passenger-side (right) mirrors were presented. However, a considerable amount of potentially useful information on mirror aiming and fields of view was not available in that report. For example, the widths of individual fields of view, the distributions of physical mirror orientations, individual eye locations, and the visual aim of the mirrors were not presented.

The current study was conducted to obtain more complete information about driver mirror aim and fields of view. Mirror fields of view (FOV) of forty-three men and women were recorded as they sat in their own passenger cars. Measurements of FOV were obtained interactively by an investigator who moved a sighting pole along an arc behind the vehicle. Projected FOV measurements were obtained by recording the three-dimensional locations of the mirror surfaces and the drivers' eye locations using a FARO Arm digitizer. FOV measurements were made with the mirrors aimed as they were when the drivers arrived for testing, and also after the drivers reaimed their mirrors to their preferred orientations.

Method

Participants

Forty-three men and women were recruited via newspaper advertisement in four age/gender categories. Table 1 shows the sampling by category. Younger drivers were aged 18 to 35, while Older drivers were age 60 or above. All participants were licensed drivers who were tested in the vehicle they normally drive. Table 2 summarizes the driver anthropometry by group. Participants were paid $20.

Table 1
Driver Sampling

	Younger 18-35 years	Older 60+ years
Male	10	11
Female	11	11

Table 2
Driver Anthropometry
(min-mean-max)

Gender	Age	Stature (mm)	Weight (kg)	Erect Sitting Height (mm)
Male	Younger (18-35)	1642-1778-1940	63-82-113	852-904-988
Male	Older (60+)	1670-1739-1868	65-82-101	840-886-983
Female	Younger (18-35)	1508-1641-1717	42-64-103	790-866-895
Female	Older (60+)	1499-1568-1688	50-63-88	757-792-839

Experimental Setup

Testing was conducted in a high-bay facility into which the participants could drive. A stall for the vehicle was prepared as shown in Figure 1. Two traffic cones were placed on each side of the stall to mark the desired location of the vehicle. A circular arc with a five-meter radius was marked on the floor with measurement tape. The measurement tape, shown in Figure 2, was marked with millimeter increments.

The three-dimensional locations of points on the driver and vehicle were measured using a FARO Arm coordinate measurement device, shown in Figure 3. The FARO Arm is constructed of three articulating arms with angle sensors at the joints. The arm reports the location of the probe tip when a button is depressed. Coordinate systems for FARO Arm measurements were established on the floor on both sides of the stall near the location of the vehicle front doors. The horizontal axes of these coordinate systems were aligned using manual measurements, and the offsets between the origins were measured. In each case, X is positive rearward relative to the vehicle, Y is positive to the right, and Z is positive upward.

Prior to measurement with the FARO Arm, the platform supporting the arm was placed under the edge of the vehicle and jacked up slightly to wedge the platform between the floor and the vehicle. The data collection coordinate system was then aligned with the adjacent floor-mounted coordinates by digitizing three points defining the origin and the X and Y axes. The origin location was verified several times during each measurement period to confirm that the FARO Arm had not inadvertently shifted.

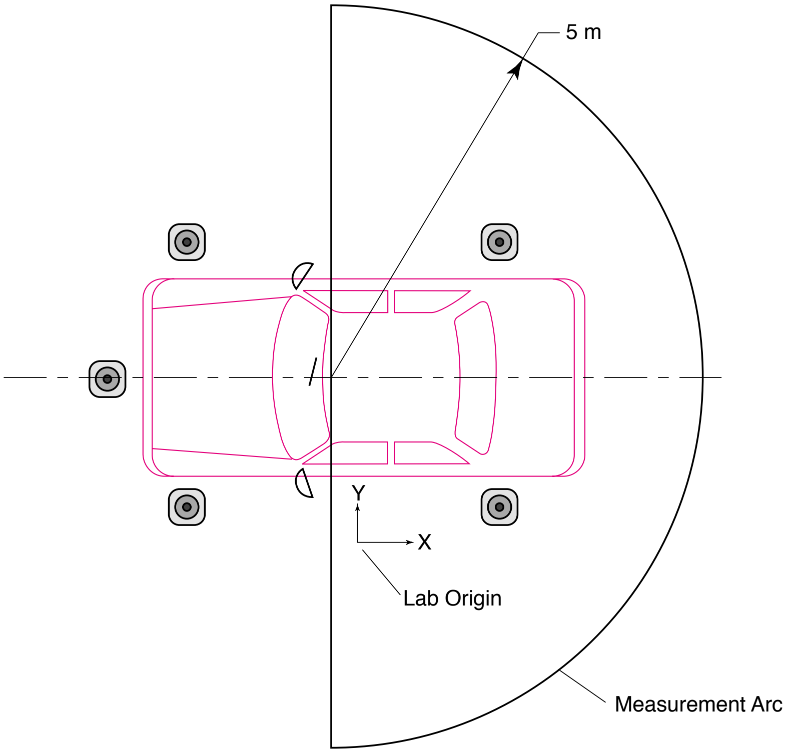


Figure 1. Schematic of measurement stall (top view).

Figure 2. Measurement tape and sighting pole.

Figure 3. FARO Arm coordinate measurement machine used to record vehicle geometry and driver eye locations.

Procedure

The participants were recruited for a "Driver Vision Study" using ads that did not mention mirrors. Participants were instructed to report for testing in vehicles they normally drove. When the participants arrived, they were directed to pull their vehicles into the test area, but the they were not told that the measurements would involve their mirrors until after they had parked in the test stall and exited the vehicle. At that time, the test procedures were explained and written informed consent was obtained. A small number of anthropometric dimensions, listed in Table 3, were measured on each driver. Descriptive information concerning the driver's vehicle and mirrors were recorded at this time. Instructions to the participants during testing were scripted to ensure uniformity. Appendix A lists the interaction script.

Table 3
Anthropometric Measurements

Stature (without shoes)
Weight (without shoes)
Erect Seated Eye Height
Erect Sitting Height
Corner Eye Breadth
Interpupillary Distance

While the driver was out of the vehicle, the investigator digitized the vehicle interior geometry. Three digitizing targets were taped to the outside of the vehicle, two near the top and bottom of the B pillar and one at the top of the A pillar. The locations of these reference points were recorded each time the FARO arm was used to provide a way of aligning the data. Points were recorded defining the locations of the steering wheel, accelerator pedal, brake pedal, instrument panel, and shifter. Four points were recorded on the inside door sill to define the X (longitudinal) axis of the vehicle.

When the driver returned to the vehicle, FOV measurements were taken. Figure 4 shows the investigator with the sighting pole instructing the driver on the measurement procedures. Beginning with the left mirror, the investigator first located the approximate center of the FOV by sighting the driver's eyes in the mirror while standing along the measurement arc. The investigator then interacted verbally with the driver to locate the top and bottom of the FOV at that lateral position by sliding visual targets on the measurement pole (see Appendix A for the participant instruction script). Drivers were instructed to use both eyes and to indicate the point at which the target was centered on the edge of the field of view. The vertical positions of the FOV boundary targets were manually recorded.

Figure 4. Investigator with measurement pole giving participant instructions.

A single target was then located on the pole at the midpoint between the top and bottom FOV boundaries. The investigator interactively determined the left and right edges of the view boundary by moving along the measurement arc with the pole. The drivers reported the boundary condition that defined their FOV, such as the edge of the mirror, edge of the window, or edge of the vehicle. The edge of the FOV was read from the scaled tape on the measurement arc and manually recorded. The FOV for the center and right mirrors was measured using the same techniques.

Following the FOV measurements, the driver's head and eye locations were recorded using the FARO arm. The investigator began by digitizing the locations of the external reference points taped to the vehicle. The locations of these points, recorded with the driver sitting in the vehicle, were used as the target reference point locations.

Data collected at other times (such as when the driver was out of the vehicle) were aligned via the reference points to the locations obtained with the driver in his or her normal driving position. This procedure accounted for the slight shifts in vehicle attitude that resulted when the driver entered or exited the vehicle.

With the driver in a normal driving position and looking straight ahead, the investigator digitized the glabella, left infraorbitale, left corner of eye, and left tragion landmarks, as shown in Figure 5. The driver looked in the left, center, and right mirrors in turn, each time prompted by the investigator to look in the mirrors as he or she had during the FOV data collection. The same four landmark locations were recorded. The driver then turned his or her head maximally to the left, so that the investigator could record the right tragion, right corner of eye, and right infraorbitale, in addition to the other four points. These data provide the necessary description of where both eyes were located with respect to the landmarks on the left side of the head.

The driver then exited the vehicle while the mirror geometry was measured. The investigator recorded approximately thirty points around the perimeter of the center and left mirrors, each time recording the three external reference points as well. The investigator then moved to the right side of the vehicle, and recorded the perimeter of the right mirror and points on the right door sill with respect to the floor-based coordinate system established on the right side of the vehicle. Using the measured relationship between the two coordinate systems, the data from the right side were combined with those from the left. Following the FARO Arm measurements, the driver was invited to reaim the mirrors to his or her preferred orientations. The resulting FOV in each mirror was measured as before. The driver was then asked seven questions concerning mirrors and mirror adjustments. The questionnaire is reproduced in Appendix B.

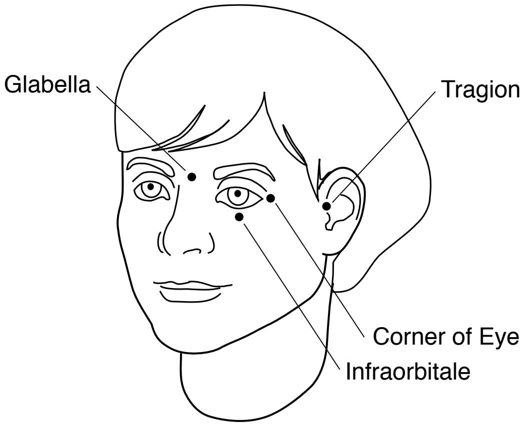


Figure 5. Head landmarks.

FOV Analysis

FOV boundaries measured using the pole-sighting technique were converted to laboratory coordinates using the geometry depicted in Figure 1. For analysis purposes, all data, including driver head locations and vehicle interior geometry, were expressed relative to an origin at the left side of the vehicle. In-vehicle data, such as mirror perimeters, were adjusted to the vehicle attitude measured with the driver in his or her normal driving position using the taped-on reference points.

Driver eye locations were calculated beginning with the landmark data collected with the driver's head turned to the left. An origin was established at the midpoint between the tragion landmarks, with the intertragion vector defining the Y axis, the Z axis defined vertically, and the X axis defined forward through the head. The eye points were then calculated using the X (fore-aft) and Y (lateral) coordinate of the infraorbitale landmark and the Z (vertical) coordinate of the corner-eye landmark. These eye points lie approximately at the center of the orbit, i.e., the approximate pivot center for the eyeball. The relationship between the two eye points and the glabella, left infraorbitale, and left tragion landmarks was stored, so that the locations of the latter three points could be used to calculate the eye locations using the landmark data recorded while the driver looked straight ahead and into each of the mirrors. Eye points for views in each of the three mirrors were calculated by this method for use in FOV calculations.

Using a least-squares approach, planes were fit to the perimeter points on the left and center mirrors recorded with the FARO Arm. Center mirrors were all day/night prisms. Calculations assumed that the front surface was angled 3.58 degrees relative to the back surface (mirror thinner at the top edge) and the center thickness was 5 mm. Ray reflection/refraction algorithms written for use with the prism mirrors assumed that the index of refraction for transition between air and glass was 1.514. Projected (effective) eye points for the left and center mirrors were calculated by reflecting the measured eye locations behind the plane of the mirror. Figure 6 shows the effective eye points schematically for the left mirror. The effective eye point can be viewed as the perceived location of the eye relative to the indirect visual field. For planar mirrors, rays from the eye points through the perimeter of mirror define the FOV in the mirror.

The right mirrors were all spherical. A calculation program was written to reflect rays from the eye points in the mirrors, with the mirrors defined using the measured perimeter points and radius (see Results).

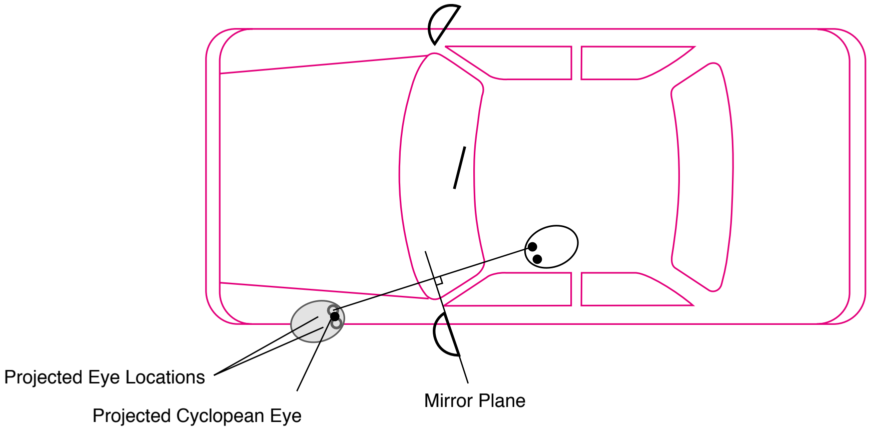


Figure 6. Method for calculating projected (effective) eye points.
Cyclopean eye point is the midpoint between the two eye points.

Results

Vehicle and Mirror Descriptions

Table 4 lists the vehicles by manufacturer. Vehicles manufactured by General Motors were most common (seventeen cars), and four companies were represented by a single vehicle. The oldest vehicle was a 1989 model year, the newest was 1999, and the median model year was 1994. Of the forty-three vehicles, two did not have right-side mirrors (1989 and 1994 model years). All right side mirrors were spherical, all left-side mirrors planar, and all inside mirrors day/night prisms. Twenty-six vehicles had electrical adjusters for the side mirrors, while seventeen vehicles had only manual adjusters.

Table 4
Vehicles by Manufacturer

Manufacturer	Number of Vehicles
General Motors (Buick, Oldsmobile, Chevrolet, Geo)	17
Ford (Ford, Mercury)	8
Honda	7
Toyota	7
DaimlerChrysler (Dodge)	1
Mitsubishi	1
Nissan	1
Volkswagen	1

Table 5 shows the distribution of mirror dimensions, measured in the plane of the mirror perimeter. The locations of the mirrors (centroid of the mirror perimeter points) with respect to the driver's cyclopean eye point when looking straight ahead are also listed, as are the mirror heights with respect to the ground plane. The average driver eye height above the ground when looking straight ahead was 1088 mm (standard deviation 49 mm). The right mirror radii were measured on thirty-six vehicles. The average right mirror radius was 1098 mm (minimum 972, maximum 1504). As expected, all were within the 889 to 1651 mm requirements of FMVSS 111, although some of the more extreme measurements may have been in error.

Table 5
Mirror Dimensions and Locations (mm)

Dimension	Mean	S.D.	Median	10th %ile	90th %ile
Left Mirror					
Width†	168	10.7	170	156	178
Height†	95	6.6	96	85	103
Fore-aft Position re Eye	-553	71.9	-551	-635	-434
Lateral Position re Eye	-523	29.6	-520	-558	-488
Vertical Position re Eye	-149	35.1	-145	-198	-109
Height Above Ground	939	33.8	935	903	989
Center Mirror					
Width	237	16.1	236	216	251
Height	57	5.0	56	51	63
Fore-aft Position re Eye	-374	65.1	-372	-467	-302
Lateral Position re Eye	334	34.6	330	292	384
Vertical Position re Eye	99	33.7	103	60	142
Height Above Ground	1187	30.7	1188	1143	1226
Right Mirror *					
Lateral Position re Eye	1209	63.2	1193	1158	1290

* Except for the lateral position, the values for the right mirror are nominally identical to those measured for the left mirror (assuming symmetrical positioning of the left and right mirrors on the vehicle) except that two vehicles were missing right mirrors.

Mirror Fields of View

The coordinates of the pole locations defining the FOV for each mirror were expressed in the same coordinate system used to calculate the effective eye points (see Figures 1 and 6). The FOV angles were then calculated relative to the average (cyclopean) eye location. The angles were adjusted to account for any deviation between the vehicle X-axis, as defined by the longitudinal orientation of the door sill, and the laboratory coordinate system. These adjustments were typically less than two degrees.

Tables 6, 7, and 8 list summary values for FOV measurements. The variables listed in the tables are defined in Table 9 and illustrated in Figure 7. The horizontal angle measures are relative to the vehicle longitudinal axis. A vertical angle of zero refers to a horizontal sight line, and a lateral angle of zero refers to a sight line parallel to the vehicle longitudinal axis. Outward lateral angles (to the left of the vehicle) are negative, and angles downward from the horizontal are negative. Figure 8 shows plots of the cumulative left, right, top, and bottom edges for the initial FOV measurements for the left mirror. Figures 9 and 10 show similar plots for the center and right mirrors. The plots include normal approximations to the data and comparison data from Olson and Winkler (1985).

The revised normal approximations in the plots were obtained using means and standard deviations calculated after deleting the four most extreme values on either end, leaving the central thirty-five values (thirty-three for the right mirror). Removing these points from the calculation improved the fit of the normal approximation to the remaining data. Table 10 lists the means and standard deviations calculated by this method.

Some adjustments to the Olson and Winkler data were necessary to obtain comparable values. In the original publication, the Olson and Winkler angle data were referenced to a point at the inside edge of the left-mirror FOV, that is, zero horizontal angle for the left mirror was defined by the vehicle edge, rather than the mirror location. This probably accounts for the offset in the inside edge values relative to the current data in Figure 8, although it also suggests that the excellent agreement at the outside edge may be misleading. The vertical angle data in Olson and Winkler were referenced to zero degrees at the ground 19 feet (5.8 m) behind the driver's eyes. The average mirror heights measured in the current study were used to adjust the values to be comparable. The horizontal angle data for the right mirror were substantially different from those measured in the current study, partly due to the difference in reference angles and because the Olson and Winkler data included both plane and spherical mirrors. In the Olson and Winkler sample of 413 vehicles, 181 had flat right-side mirrors, 228 had convex mirrors, and four right-side mirrors were missing. To obtain comparable values, the horizontal FOV data for the right mirror from Olson and Winkler were shifted to match the current data with respect to the mean inside edge of the FOV.

Table 6
Summary of FOV in LEFT Mirror
(angles in degrees with respect to the horizontal, longitudinal,
rearward-directed vehicle axis)

Dimension	Mean	S.D.	Median	10th %ile	90th %ile
Outside (Left) Edge	-14.0	5.2	-14.3	-19.3	-6.6
Inside Edge	-1.1	4.5	-1.0	-6.3	2.6
Top Edge	3.3	1.9	3.5	1.0	5.8
Bottom Edge	-3.9	2.5	-3.9	-6.6	-1.5
Horizontal Field	12.9	2.8	12.5	9.7	16.2
Vertical Field	7.3	1.5	7.7	6.2	8.6
Horiz. Field (Calc.)	16.3	1.3	16.5	14.5	18.0
Vert. Field (Calc.)	7.5	0.9	7.5	6.4	8.4
Horizontal Angle	17.8	2.7	17.9	13.8	21.2
Vertical Angle	6.3	1.4	6.2	4.9	7.8
Horizontal Aim	-4.6	4.4	-4.8	-8.8	0.5
Vertical Aim	0.0	2.0	-0.1	-2.1	2.4

Table 7
Summary of FOV in CENTER Mirror
(angles in degrees with respect to the horizontal, longitudinal, rearward-directed vehicle axis)

Dimension	Mean	S.D.	Median	10th %ile	90th %ile
Left (Driver-Side) Edge	-6.9	2.9	-7.1	-10.5	-4.3
Right Edge	18.4	3.2	19.0	13.7	21.8
Top Edge	4.8	0.9	5.0	3.8	5.9
Bottom Edge	-0.4	0.8	-0.3	-1.4	0.4
Horizontal Field	25.3	3.5	25.0	21.0	29.8
Vertical Field	5.2	0.8	5.2	3.9	6.1
Horiz. Field (Calc.)	33.5	3.9	32.7	29.1	38.2
Vert. Field (Calc.)	6.7	1.1	6.6	5.4	7.5
Horizontal Angle	-18.6	3.1	-18.5	-22.2	-14.3
Vertical Angle	-12.0	2.0	-12.2	-14.6	-9.4
Horizontal Aim	4.3	4.3	4.0	-0.4	10.9
Vertical Aim	0.9	2.2	0.9	-2.1	3.6

Table 8
Summary of FOV in RIGHT Mirror
(angles in degrees with respect to the horizontal, longitudinal, rearward-directed vehicle axis)

Dimension	Mean	S.D.	Median	10th %ile	90th %ile
Inside (Left) Edge	-2.8	2.4	-2.8	-5.9	0.2
Outside Edge	19.8	5.7	19.9	12.1	26.3
Top Edge	5.9	3.2	6.2	1.8	9.7
Bottom Edge†	-7.9	2.9	-8.2	-11.5	-4.4
Horizontal Field	22.5	5.0	23.3	15.8	27.6
Vertical Field	13.8	2.4	13.9	11.4	16.1
Horiz. Field (Calc.)	26.6	3.1	26.9	22.9	29.1
Vert. Field (Calc.)	12.9	1.3	12.8	11.4	14.5
Horizontal Angle	-51.0	2.2	-51.0	-54.0	-48.1
Vertical Angle	-17.8	1.9	-18.0	-19.8	-15.6
Horizontal Aim	8.6	5.4	9.3	1.6	14.1
Vertical Aim	-1.4	2.9	-1.1	-5.2	2.1

† The bottom edge angle in the right mirror was sometimes limited by the floor at measuring position. Some drivers could see the floor in the right mirror at distances closer than the measurement arc, and hence had downward FOV boundaries less restrictive than the reported angles.

Table 9
Definition of Variables Describing Field of View

Variable	Definition
Inside (Left / Driver-Side) Edge	Angle with respect to rearward longitudinal axis of the vehicle of the edge of the field of view; calculated using the vector from the projected cyclopean eye point to the FOV boundary on the measurement arc. For right mirror, angle is calculated using the vector from the FOV boundary point to the corresponding edge of the mirror.
Outside Edge	Complement to the Inside Edge.
Top Edge	Angle with respect to horizontal of the top edge of the field of view; calculated using the vector from the projected cyclopean eye point to the FOV boundary on the measurement arc. For right mirror, angle is calculated using the vector from the FOV boundary point to the top of the mirror. Measurement is made at the center of the lateral FOV.
Bottom Edge	Complement to Top Edge.
Horizontal Field	Angular width of horizontal FOV, based on pole-sighting FOV measurements referenced to projected cyclopean eye; difference between left and right edge angles.
Vertical Field	Angular width of horizontal FOV, based on pole-sighting FOV measurements referenced to projected cyclopean eye; difference between top and bottom edge angles.
Horiz. Field (Calc.)	Angular width of horizontal ambinocular FOV, based on reflections of rays from both eye locations through points on the mirror perimeter. This is the actual FOV given by the mirror; because of interference from vehicle structure, the FOV behind the vehicle, described by the pole-sighting measurements, is generally smaller. The difference between Horiz. Field (Calc.) and Horizontal Field is a measure of the amount of how much of the vehicle the driver can see in the mirrors.
Vert. Field (Calc.)	Analogous to Horiz. Field (Calc.)
Horizontal Angle	Angle in the horizontal plane of a vector perpendicular to the face of the mirror (left and center mirrors) or perpendicular to a plane fit to the perimeter points (right mirror); a measure of the orientation of the mirror.
Vertical Angle	Analogous to Horizontal Angle
Horizontal Aim	Center of the calculated cyclopean horizontal FOV, obtained by reflecting rays from the cyclopean eye point through the perimeter points on the mirror. This angle can be interpreted as the visual aim of the mirror, i.e., the vector angle that lies in the center of the mirror FOV.
Vertical Aim	Analogous to Horizontal Aim

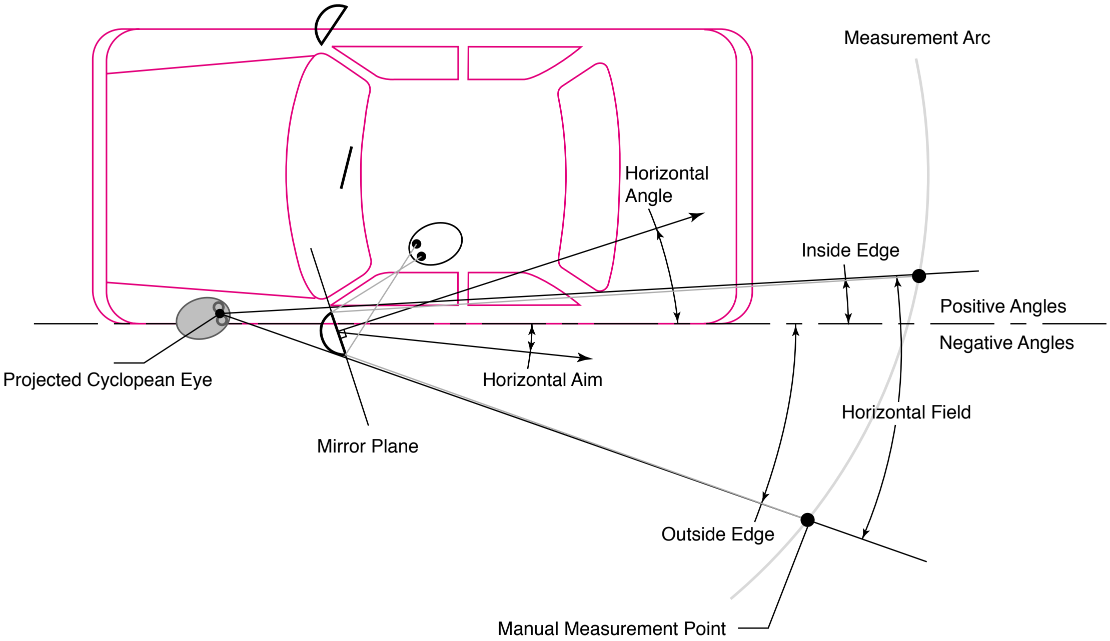
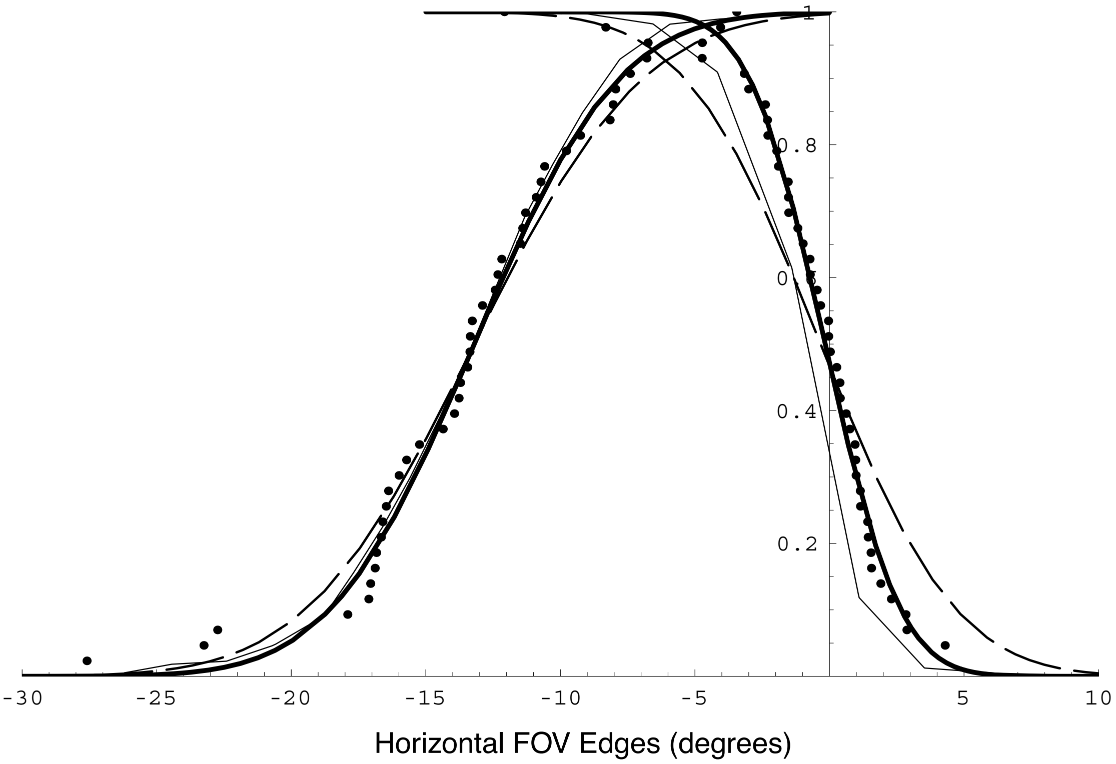


Figure 7. FOV measurement definitions. Vectors from the projected cyclopean eye point to the pole-sighting FOV measurement points do not necessarily pass through the perimeter of the mirror, but the angles measured in this way are very similar to the true FOV angles (shown with gray lines).



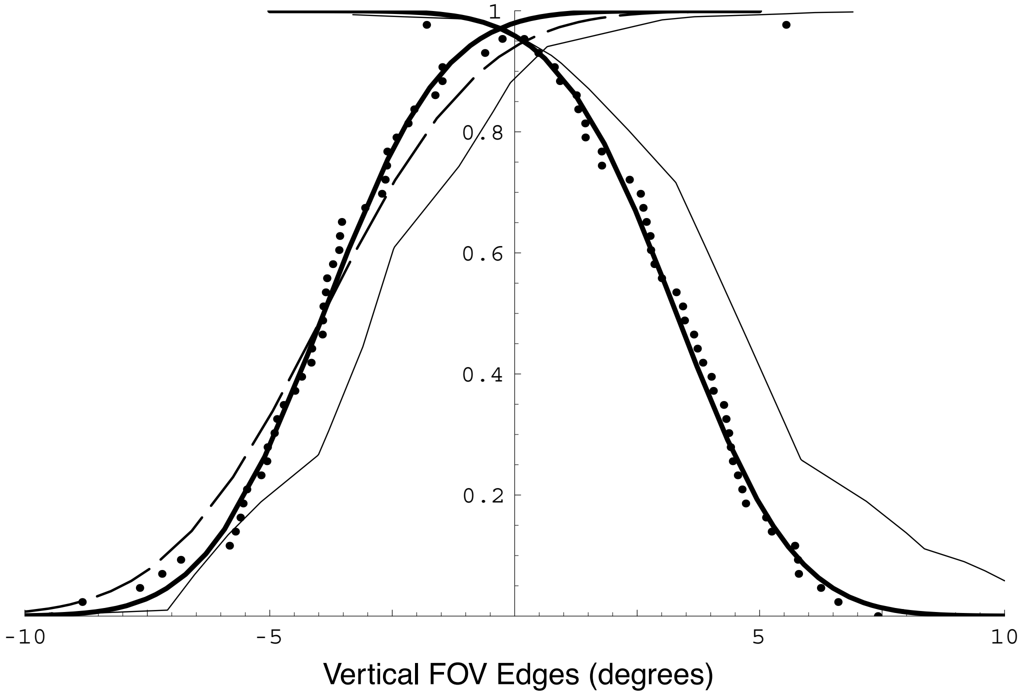


Figure 8. Cumulative left, right, top, and bottom edges of the FOV in the LEFT mirror (points), normal approximation (dashed lines), revised normal approximation (see text) after deleting the four most extreme values on both ends (thick lines), and Olson and Winkler (thin lines).

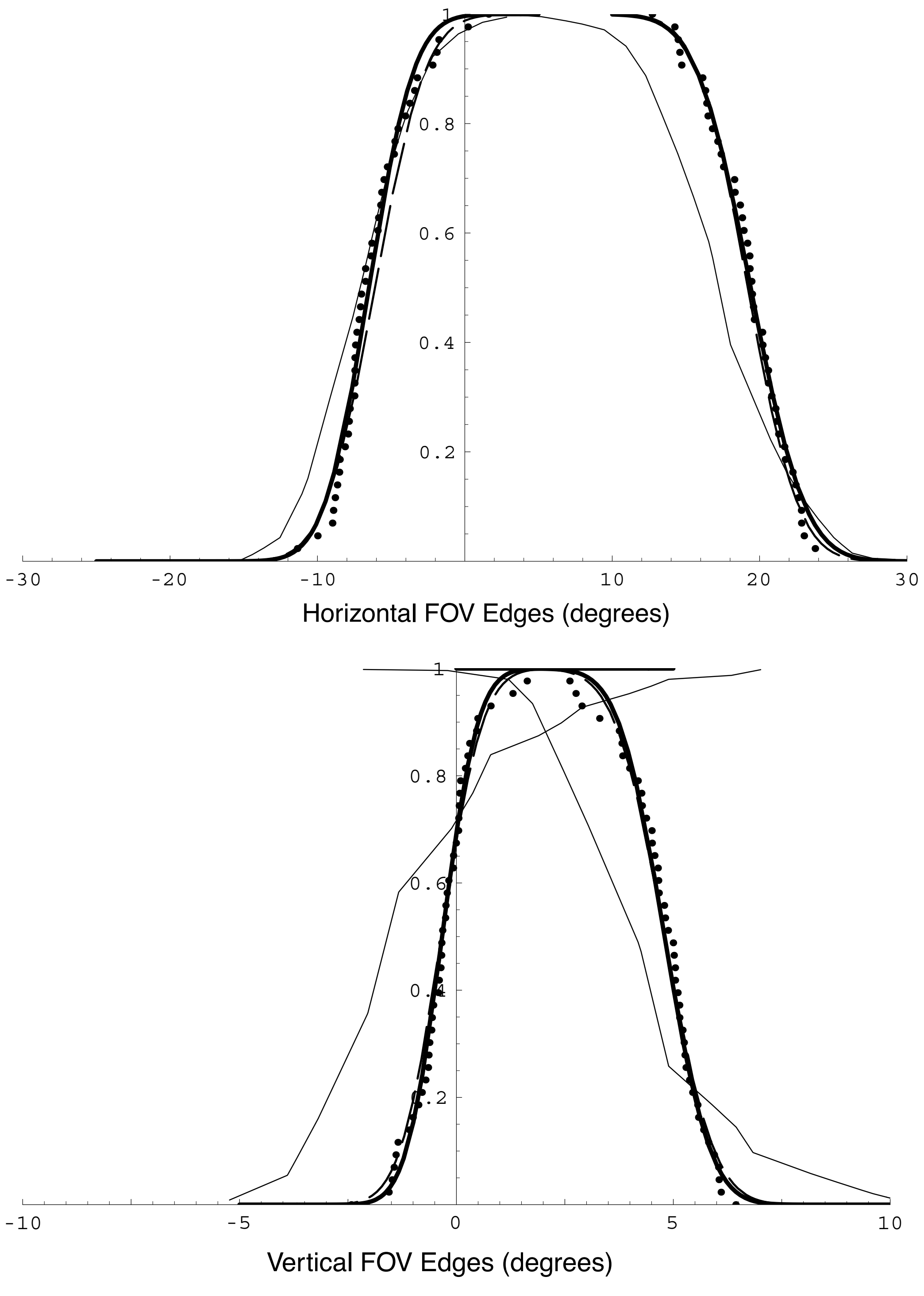
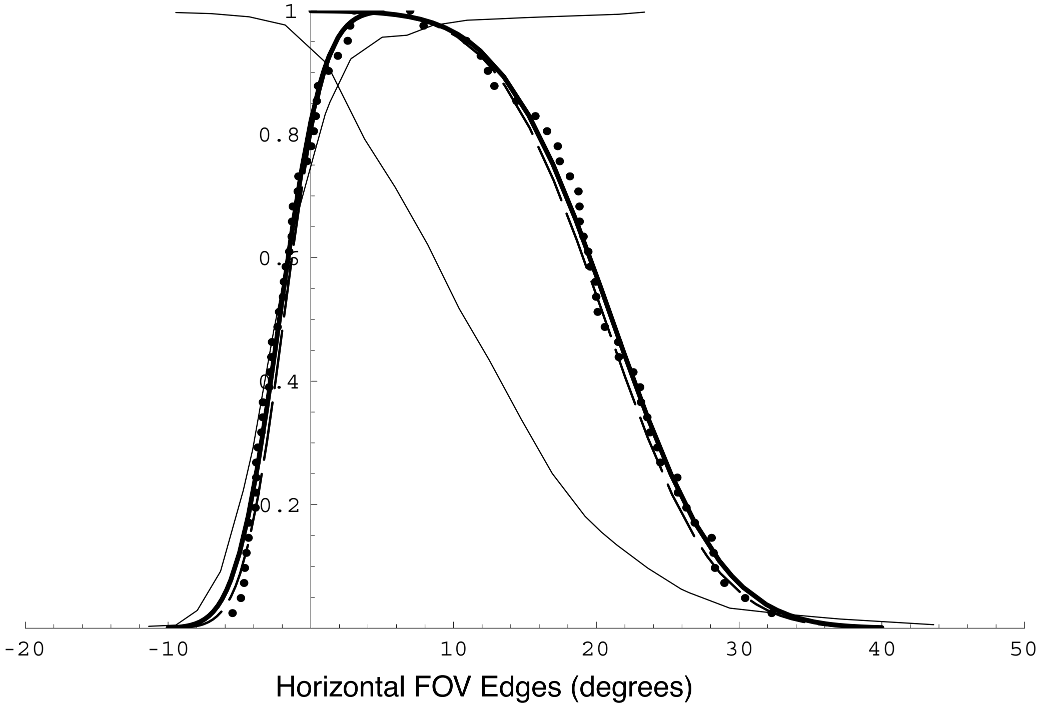


Figure 9. Cumulative left, right, top, and bottom edges of the FOV in the CENTER mirror (points), normal approximation (dashed lines), revised normal approximation (see text) after deleting the four most extreme values on both ends (thick lines), and Olson and Winkler (thin lines).



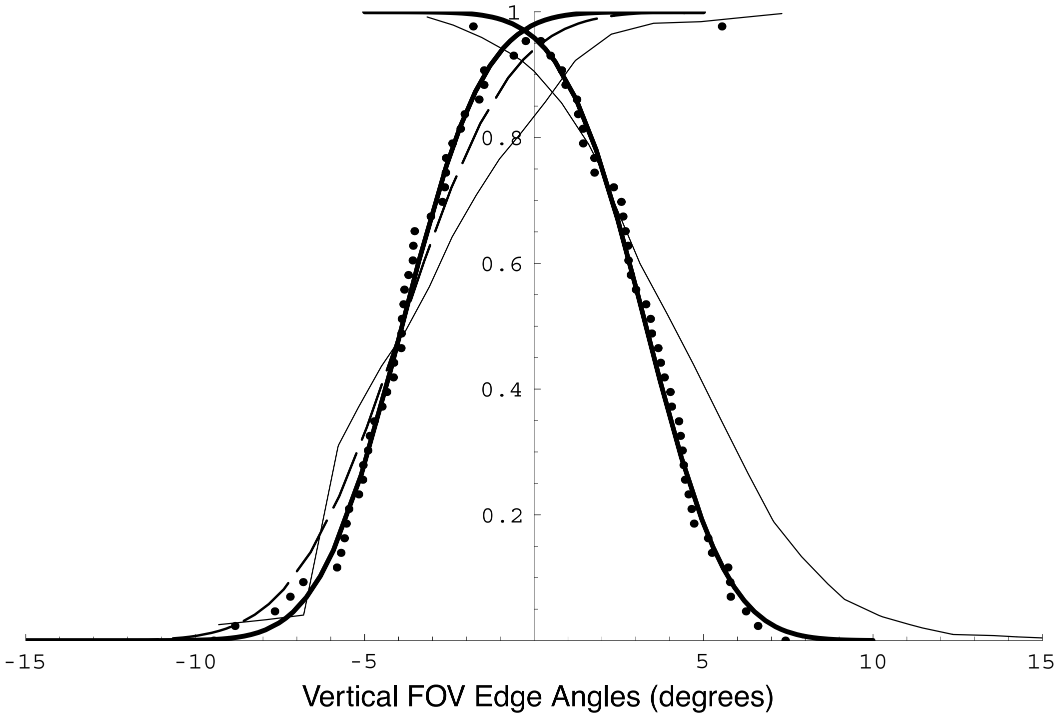


Figure 10. Cumulative left, right, top, and bottom edges of the FOV in the RIGHT mirror (points), normal approximation (dashed lines), revised normal approximation (see text) after deleting the four most extreme values on both ends (thick lines), and Olson and Winkler (thin lines).

Table 10
Means and Standard Deviations (degrees) Used for
Revised Normal Approximations in Figures 8, 9, and 10

Mirror	Edge	Mean	S.D.
Left			
	Outside	-13.2	4.2
	Inside	-0.2	2.2
	Top	3.3	1.9
	Bottom	3.9	1.9
Center			
	Left	-6.5	2.4
	Right	19.4	2.9
	Top	4.8	0.8
	Bottom	-0.3	0.7
Right			
	Outside	21.1	6.1
	Inside	-2.2	2.4
	Top	5.8	3.4
	Bottom	-8.0	3.0

Reaim

Table 11 lists summary statistics for measurements obtained after the drivers reaimed their mirrors. Only the left-mirror outer edge is significantly different from the original measurements, using a within-subjects analysis. The average left-mirror outer-edge angle was –15.1 degrees after the reaim, compared with –14.0 degrees initially. Figure 11 illustrates that the difference is primarily due to a few drivers who aimed their mirrors more outward during reaiming. Mirror aim and calculated FOV measures are not available for the reaim because the mirror surfaces were not redigitized. However, since only one of the FOV variables differed significantly, it is unlikely that the variables based on digitized data would have changed substantially after the reaim.

Table 11
Reaim FOV Measures

Dimension	Mean	S.D.	Median	10th %ile	90th %ile
Left Mirror					
Left (Outside) Edge	-15.1*	4.3	-15.3	-19.6	-9.8
Right Edge	-1.6	3.3	-1.5	-5.4	2.3
Top Edge	3.5	2.0	3.7	1.3	5.8
Bottom Edge	-4.0	2.0	-4.1	-6.7	-1.9
Horizontal Field	13.5	2.0	13.3	11.5	15.8
Vertical Field	7.5	1.1	7.7	6.3	8.8
Center Mirror					
Left (Driver-Side) Edge	-6.5	2.9	-6.5	-9.5	-2.2
Right Edge	18.5	4.4	19.2	14.9	22.0
Top Edge	4.8	0.9	4.9	3.7	5.9
Bottom Edge	-0.3	0.8	-0.3	-1.2	0.5
Horizontal Field	25.0	4.4	25.7	21.1	28.8
Vertical Field	5.2	0.8	5.2	4.2	6.0
Right Mirror					
Left (Inside) Edge	-3.6	4.0	-3.2	-6.9	-0.7
Right Edge	20.1	5.9	20.6	13.4	25.8
Top Edge	5.5	4.0	6.7	0.9	9.5
Bottom Edge	-7.9	2.6	-7.7	-11.5	-4.6
Horizontal Field	23.8	6.8	23.8	16.5	28.1
Vertical Field	13.3	2.6	13.5	10.6	16.1

* Mean significantly different from value measured before reaim ($p<0.05$).

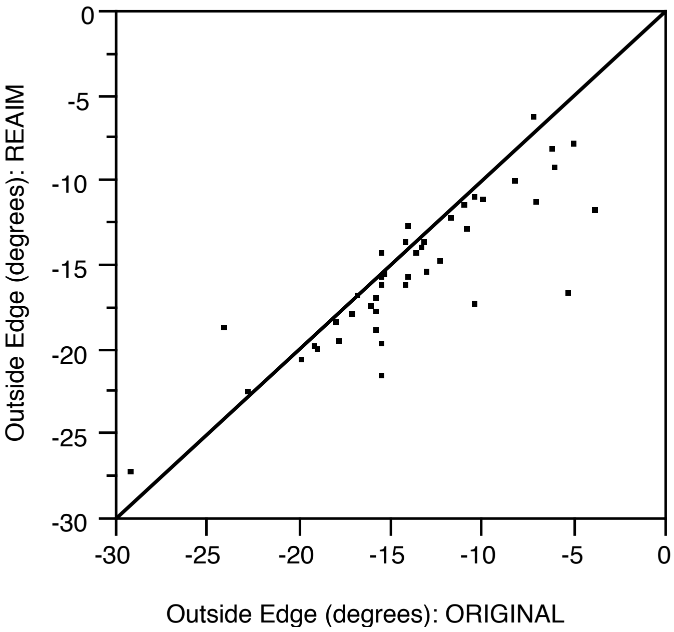


Figure 11. Original versus reaim left-mirror outside-edge angle.

Factor Effects

ANOVA detected no significant differences between age and gender groups in field of view measures or mirror aim. Linear regression analysis demonstrated only a few significant effects of body dimensions, all related to the fact that shorter drivers sit further forward with lower eye positions. Shorter drivers have slightly larger FOV in the left mirror because they sit closer to the mirror. Shorter drivers also angle the center mirror more downward, but the resulting visual aim is not significantly different from that of tall drivers (all drivers aim their view in the mirror approximately horizontal). In most respects, mirror FOV and aim are not affected by age or driver size.

Seeing Part of One's Vehicle

Most of the outside mirrors were aimed in such a way that the drivers could see their vehicles. All but seven of forty-three drivers identified the car as the limit for the inside edge of the left-mirror FOV. In the right mirror, the car defined the inside edge of the FOV for all but nine of forty-one drivers. After the reaim, the numbers did not change substantially (eight and seven, respectively).

The calculated FOV (using ray projections) was generally larger than the FOV measured using the pole-sighting technique, with the difference providing an estimate of how much of the mirror FOV was obstructed by the vehicle. On average, the measured horizontal field of view was 3.5 degrees less than the calculated field of view in the left mirror and 4.0 degrees less in the right mirror, although there was considerable variability. Given the average, horizontal, calculated FOV of 16.3 degrees on the left and 26.6 degrees on the right, drivers used an average of 21 percent (left) and 15 percent (right) of the ambinocular mirror FOV to see their vehicles.

Distributions of FOV and Mirror Variables

Mirror aim is approximately normally distributed both horizontally and vertically, a finding that may be useful for modeling. Mirror aim is also independent of mirror FOV and driver stature. Hence, horizontal FOV in the left mirror can be reasonably modeled as a field of width W centered on an angle A, with W normally distributed with mean 16.3 and standard deviation 1.3 degrees, and A normally distributed with mean –4.6 and standard deviation 4.4 degrees. The outside edges of the left and right mirror FOV are also normally distributed, with means and standard deviations shown in Tables 6, 7, and 8. Mirror edges that are restricted by vehicle structure (e.g., inside edge of left mirror) are generally not normally distributed. The coordinate data on eye location and mirror perimeter provide the opportunity for a wide range of FOV analyses. Projecting rays from the measured eye locations through points on the mirror perimeters maps out the FOV experienced by the driver, without the interference resulting from vehicle structures. Of course, the functional FOV is often restricted by the vehicle, but the calculated FOV gives a more complete picture of what the driver sees in each mirror.

Figure 12 shows the FOV in the left mirror for one driver. Separate FOV for each eye are shown. The data have been converted to angular coordinates, so that the horizontal axis displays the horizontal angle with respect to rearward, and the vertical axis displays the vertical angle with respect to horizontal. The interocular spacing is an important determinant of FOV, particularly in the left and center mirrors. Both because of sphericity and greater distance from the driver to the mirror, the interocular spacing has a smaller effect on the right mirror. In the left mirror, the binocular FOV (area which can be seen by both eyes) is usually less than half of the ambinocular FOV (the area which can be seen by either eye, that is, the union of the individual eye FOV). Drivers who sit closer to the mirror (generally smaller-statured drivers) and those who turn their heads to face directly at the mirror experience the greatest difference between left and right eye FOV.

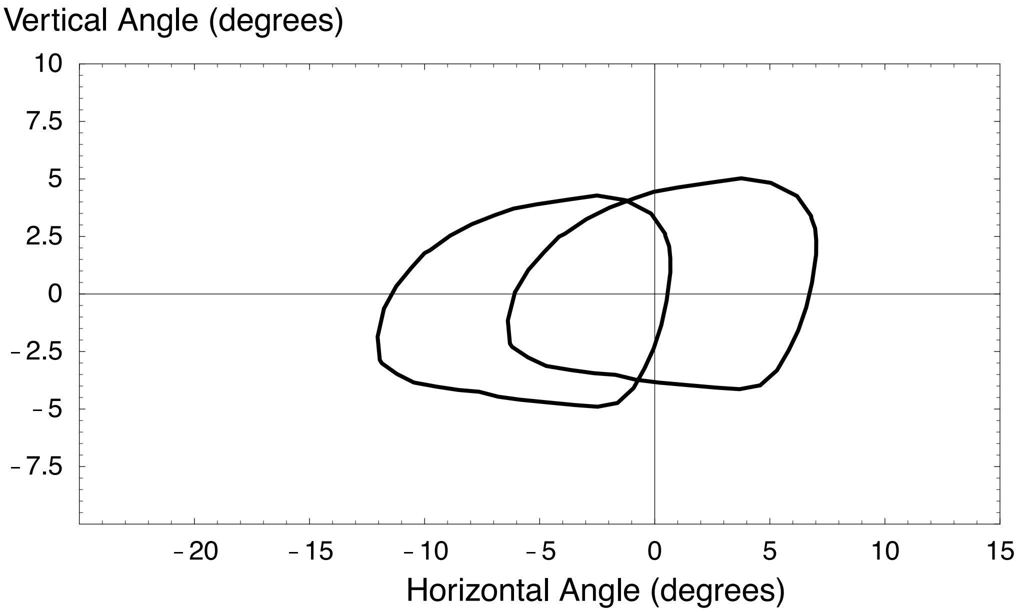


Figure 12. FOV in the left mirror for one driver, calculated by projecting rays from the eye points to through points on the mirror perimeter. Plot axes are angles in degrees, relative to the horizontal, longitudinal vehicle axis. Positive hoirzontal angles are inboard (toward the vehicle). FOV for the right eye is on the left (more outboard).

The calculated mirror FOV can be combined across drivers to describe the population density in the angular FOV space. Figure 13 shows FOV in the left mirror for all drivers, using projections of rays from the eye points through the mirror perimeter points. If these data are superimposed on a grid of points in angular FOV space, the percentage of drivers who can see any particular point in the FOV space can be determined. Figure 14 shows this density distribution as a bar plot and a smoothly interpolated surface. The height of the surface gives the fraction of drivers who could see a particular point in the angular FOV space. Since zero degrees horizontal is straight rearward from the mirror, the fact that many drivers use substantial portions of their mirror FOV to view their vehicles is evident by the large amount of the FOV density in areas of positive horizontal angles. Figure 15 shows horizontal and vertical slices through the mode of the distribution, which lies at about -4 degrees horizontal and 0 degrees vertical. Interestingly, the peak value at the mode is only 0.84, indicating that about 84 percent of drivers could see a point in angle space with horizontal angle –4 degrees and vertical angle 0 degrees. Note from Table 6 that the modal point is also approximately the same as the mean and median aim point (center of FOV) for the left mirror. Close examination of the mirror data in Figure 13 indicates that the vertical mirror FOV for some drivers did not include horizontal, even though the horizontal FOV included the mean aim value of -4.4 degrees. Since few real viewing targets are point targets, it's useful to consider the fraction of drivers who could see either a horizontal or vertical line in the angular FOV space. In other words, what percentage of drivers could see a pole located at -4 degrees with respect to the long axis of the vehicle? The thick lines in Figure 15 show the fraction of drivers whose view includes a range of horizontal and vertical angles. While only about 85 percent of drivers can see a point at -4 degrees horzontal, 0 degrees vertical, about 95 percent of drivers could see a pole located 4 degrees outboard from the left side of the vehicle. Similarly, about 95 percent of drivers' left-mirror FOV include horizontal.

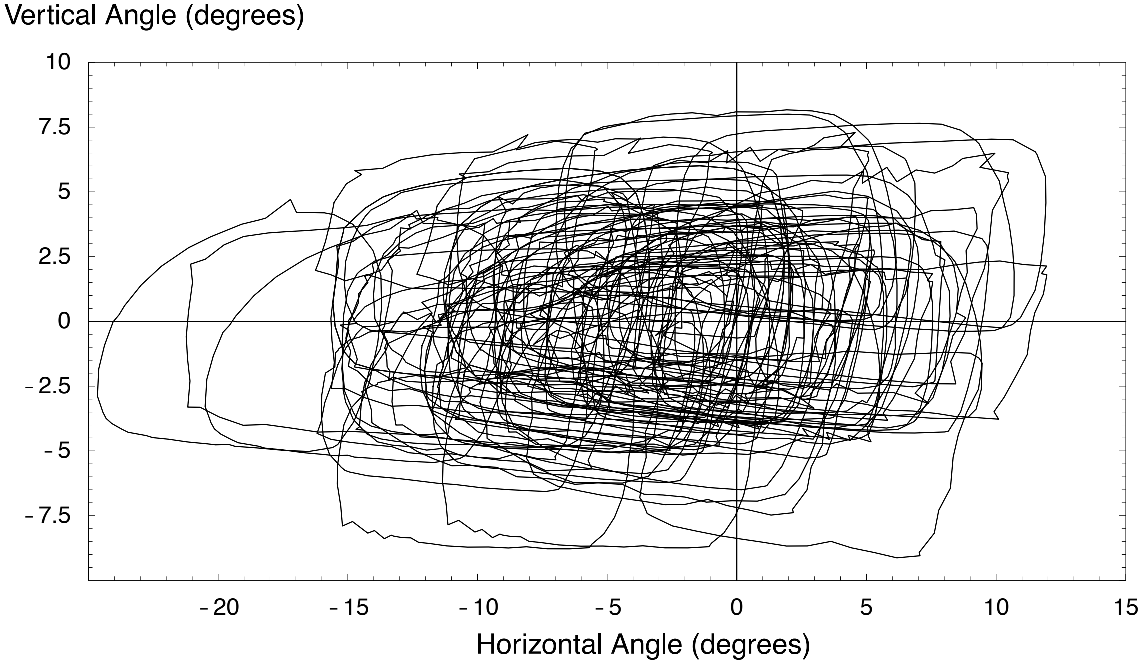


Figure 13. FOV in the left mirror for all drivers, calculated as in Figure 12. Irregular lines result from digitizing deviations on the perimeter of the mirror.

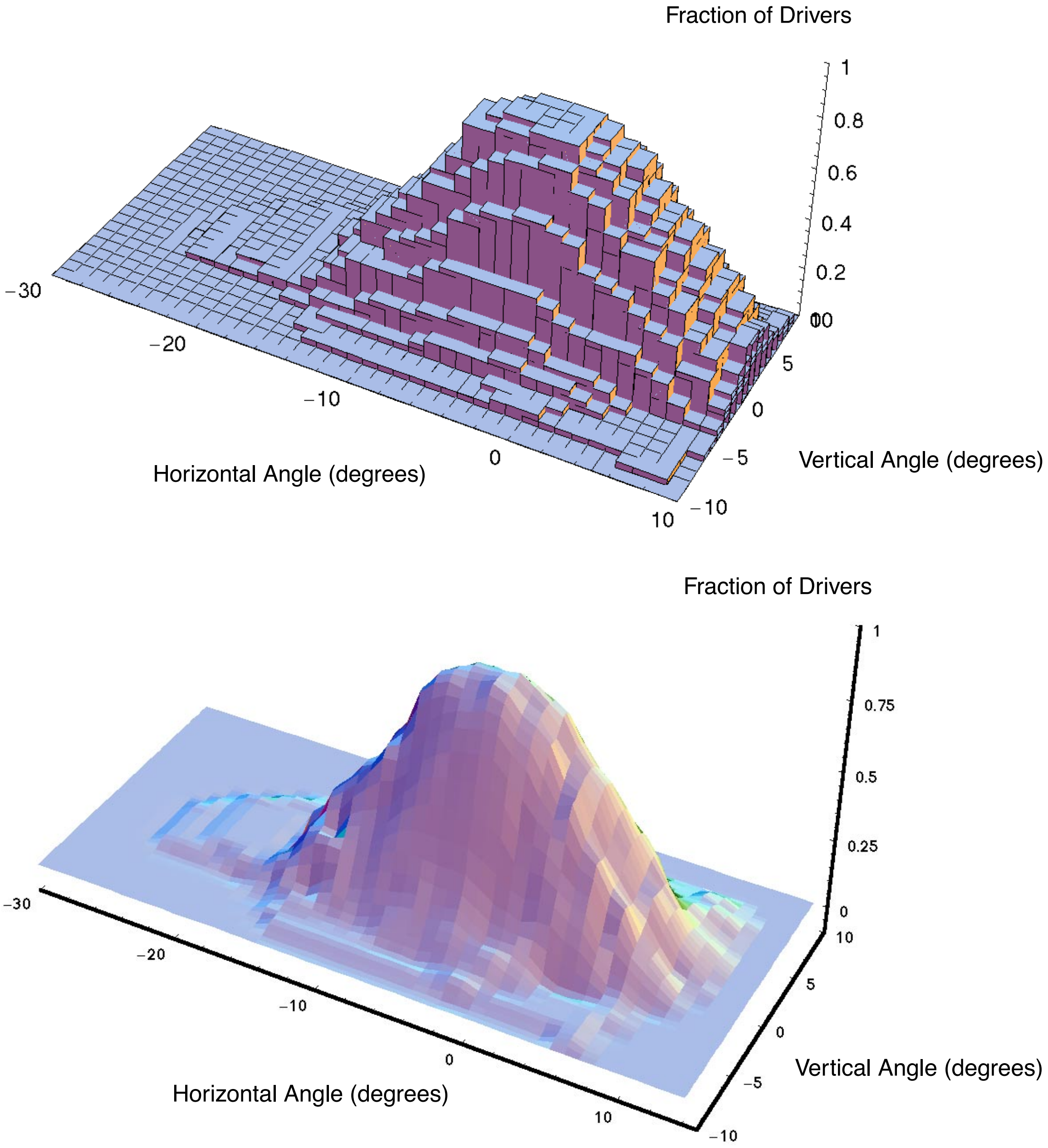


Figure 14. Density distribution of FOV in the left mirror for all drivers, showing the fraction of drivers whose FOV includes the specified point in the horizontal and vertical angular FOV space. Bottom plot is a smooth interpolation of the discrete count data from the top plot.

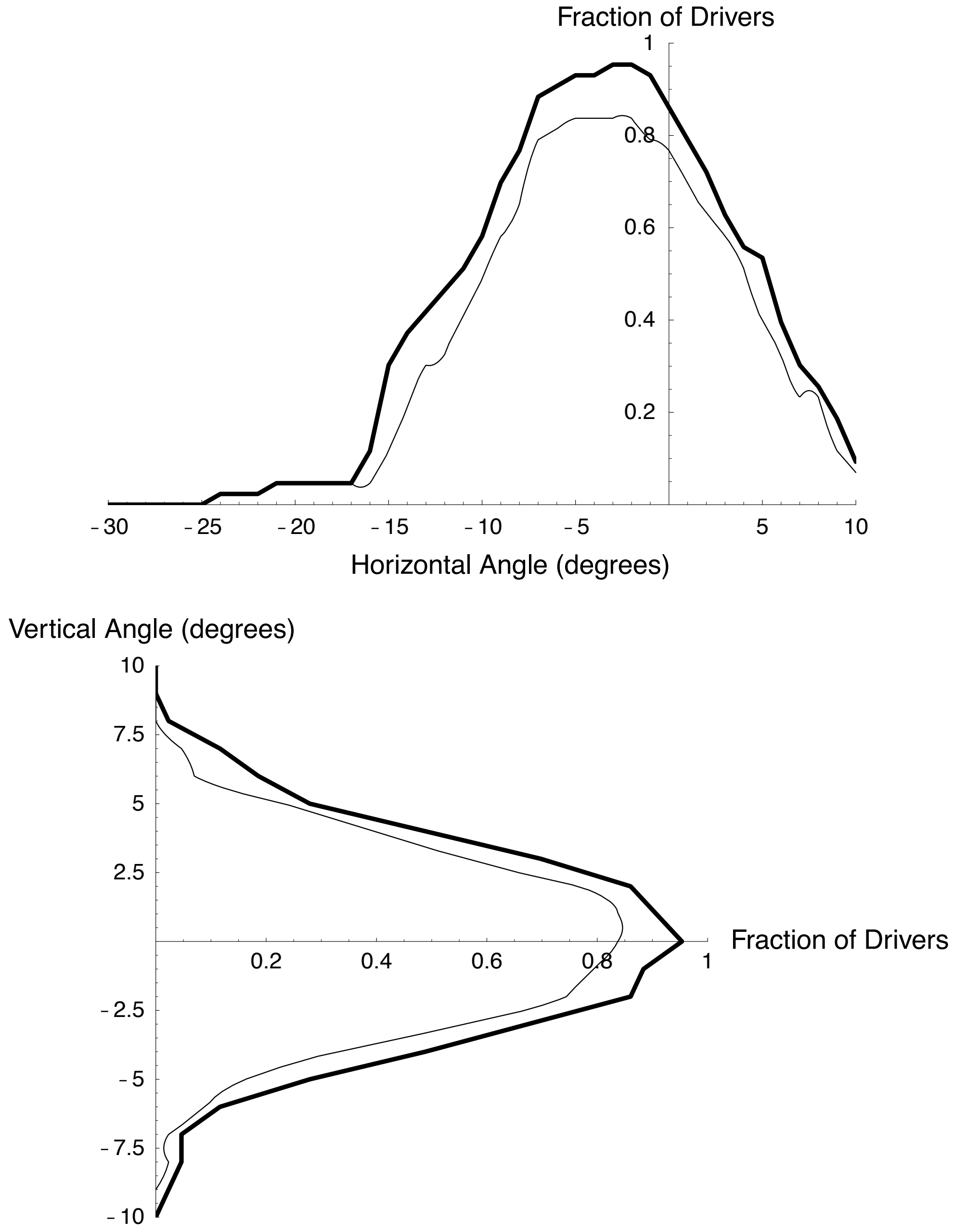


Figure 15. Fraction of drivers who can view a range of points and angles in the left-mirror FOV space. The thin lines are horizontal and vertical sections through the mode of the distribution in Figure 14, located at -4 degrees horizontal and 0 degrees vertical. Thick lines show the fraction of drivers whose FOV includes the horizontal or vertical angle, irrespective of the FOV on the other axis.

Comparison of Calculated and Measured FOV

The validity of the method for calculating FOV by projecting rays from the measured eye locations through the mirror perimeter can be evaluated by comparing the resulting FOV angles with those obtained by the pole-sighting method. The comparison is best made for the outside edges of the horizontal FOV in the side mirrors, since these angles are not delimited by the vehicle. Figure 16 compares the outside edge angles for the left and right mirrors obtained by the two methods. In general, there is strong correlation between the two values (0.86 for the outside edge of the left mirror, 0.90 for the outside edge of the right mirror). The plots in Figure 16 show that there is some bias in the calculated FOV for each mirror. The outside edge of the left-mirror FOV obtained by the pole-sighting method is an average of 1.5 degrees more outboard than the edge obtained by projecting rays from the driver's right eye location. This difference probably results from small driver head movements during the pole-sighting measurement.

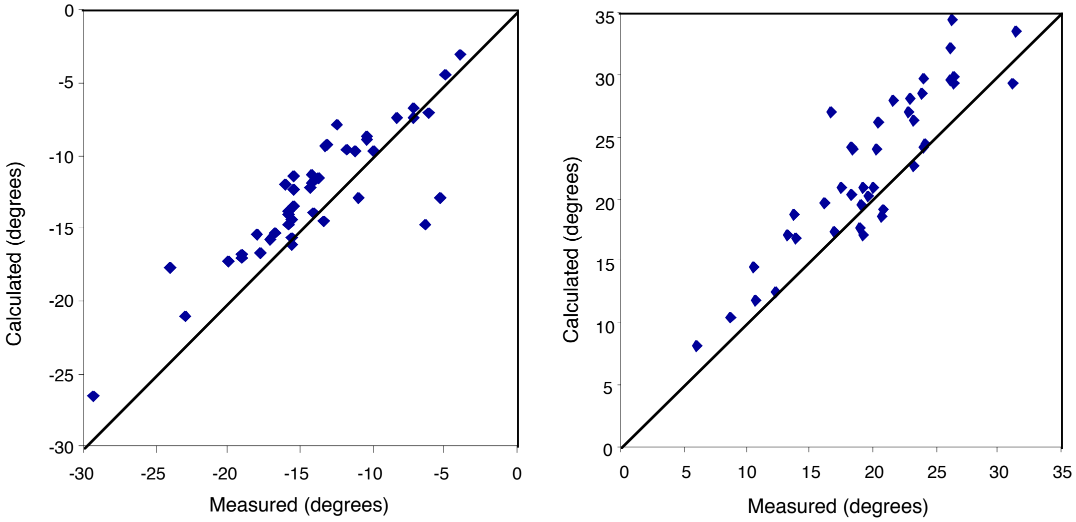


Figure 16. Comparison of FOV calculated using ray projection from measured eye locations and that measured using the pole-sighting technique for outer edges of the left-mirror FOV (left) and right-mirror FOV (right).

For comparison, Figure 12 shows that the difference in the angular FOV edges for the left and right eye of a driver is typically about 5 degrees. Since the driver's eyes are usually about 65 mm apart, a lateral head movement of only about 20 mm would be needed to produce a change in outboard FOV angle of 1.5 degrees. A bias similar in magnitude but opposite in effect is observed for the right mirror. The calculated outboard edge of the FOV in the right mirror is an average of 2.8 degrees further outboard than the angle measured by the pole-sighting method. Since head movements have smaller effects on FOV in the right mirror than in the left mirror, this difference may be due to image quality degradation at the edge of the FOV in the convex right mirrors.

Questionnaire Results

Following the data collection, participants were asked seven questions (see Appendix B for the questionnaire). The open-ended responses were categorized and tabulated as shown in Table 12. On question 1, twenty-six of forty-three drivers indicated that they use the day/night adjuster. Questions 2 and 3 were somewhat ambiguous, because some participants interpreted the questions as referring to the last time they adjusted their mirrors, rather than checked their adjustment. Approximately two-thirds of the drivers reported that they check their mirrors daily. Eighteen of the participants reported that someone else regularly drove their vehicles, and twenty-five of forty-three indicated that they needed to readjust the mirrors after someone else drove the vehicle. Many participants who indicated that no one else regularly drove their vehicles did not answer the question about reaiming.

In response to question 6, nine drivers indicated that they try to see part of their car in their side mirrors, although the aiming data suggest that a much greater percentage can see their cars. Eight drivers responded that they try to maximize their FOV or minimize blind spots, and eight said that they try to center the FOV of the inside mirror on the rear window. Ten responded “no” to this question.

Ten drivers responded affirmatively to question 7, indicating problems using their mirrors. Three reported that they were unable to adjust their outside mirrors or didn’t know how, but the other responses ranged from a durability problem with the inside mirror to general vision problems due to low eye height.

Table 12
Responses to Questions

1. Do you normally use the day/night mirror setting of your inside mirror at night?					
	Yes	No			
	26	17			
2. When was the last time, before just now, you checked the aim of your mirrors?					
	Today	< 1 Week	< 1 Month	Other	
	27	15	6	6	
3. How often do you normally check the aim of your mirrors?					
	Daily	Weekly	Monthly	Other	
	31	5	6	12	
4. Does any one else regularly drive the car you brought here today?					
	Yes	No			
	18	25			
5. If any one else drives your car, do you have to reaim the mirrors after they use it?					
	Yes	No	No Response		
	25	3	16		
6. Do you have any special strategy for aiming your mirrors?					
	No	See Part of Car in Side Mirrors	Maximize FOV	Minimize Blind Spots	Center Rear Window
	10	9	7	8	8
7. Do you have any special problems with rearview aiming?					
	No	Other			
	33	10			

Discussion

An important part of this study was the application of coordinate-measurement methods to the study of mirror FOV. Previous studies, such as Olson and Winkler (1985), used only pole-sighting measurements. In this study, these measurements were supplemented by measurements of mirror geometry and eye locations, providing a more complete picture of mirror FOV and mirror adjustment behavior.

The data for the left mirror are most interesting, for several reasons. The center-mirror FOV is usually constrained by the geometry of the back window of the vehicle, and the spherical right mirror provides a large FOV that may reduce the need to adjust it. In contrast, the FOV provided by the flat left mirror is smaller than the region of interest behind and to the left of the vehicle, so drivers must choose what portion of that area to view in their mirrors. The data show that, on average, drivers center their left-mirror FOV about 5 degrees outboard from the long axis of the vehicle. Since the average ambinocular FOV provided by the mirror is about 16 degrees, drivers are using about 20 percent of their available FOV to place the side of their vehicle in the frame (16/2 = 8; 8-5 = 3; 3/16 = 0.19). In response to an open-ended question about mirror aiming strategy, 21 percent of the drivers explicitly indicated that they try to see some of their vehicle in the mirror. Many more apparently can see part of their vehicle, because the inside edge of the left-mirror FOV, measured using the pole-sighting technique, was delimited by the vehicle for 84 percent of the drivers. This finding suggests that any attempt to improve the mirror FOV on the driver side of the vehicle must build from the inside out, since most drivers may be unwilling to select a left-mirror FOV that does not include the vehicle.

Drivers did not substantially change the aim of their mirrors when given an opportunity, indicating that the more complete data from the original aim scenario are reasonably representative of both mirror aim in actual use and driver's preferred mirror aim. Notably, those drivers who reported for testing with strongly outboard left-mirror aim generally retained it when given the opportunity to reaim, suggesting that the outward aim was part of a conscious mirror-aiming strategy.

The magnitude of the interocular FOV difference gives an idea of the importance of head movement in expanding the left-mirror FOV. Typical interocular spacing is about 65 mm. With body lean and neck movement, drivers are capable of moving their eyes over a much larger distance. By shifting their heads laterally, they can change the FOV in the left mirror substantially. Indeed, most people will recognize this in their own driving behavior. Many people will lean forward and inboard to get a better outward view in the left mirror prior to a lane change to that side. Head movements also provide a behavioral method of reducing the influence of headlight glare in the left mirror. Drivers can aim the mirror outward, so that a slight lean to the left is required to view the road directly behind the vehicle, where the headlights of following cars are located. This suggests a task-based FOV measurement. For example, when preparing to change lanes to the left, what part of the space around the vehicle is viewed in the left mirror? As a result of head movements, this visual field may be 50 percent larger for some people than the static FOV. Measurements of head movements during driving would be required to determine definitively the extent to which drivers use eye location changes to improve their mirror FOV, and whether people who have reduced neck mobility partially compensate with a different mirror aiming strategy.

This study did not find any differences in mirror aiming between men and women, younger and older, or drivers of different stature. Shorter drivers, who tend to sit further forward in the vehicle, orient the mirrors at a greater angle to the horizontal axis of the vehicle, but the resulting visual mirror aim (center of the FOV) is not significantly different from that of taller drivers. Taller drivers, whose eyes are farther away from the mirrors, experience slightly smaller FOV, particularly in the left and center mirrors.

Many of the mirror-related parameters are independent, facilitating modeling efforts. For example, the FOV width is independent of the mirror aim, and vertical aim is independent of horizontal aim. This information could be combined with the eyellipse, following the method of Flannagan and Flannagan (1998), to obtain information on the necessary adjustment ranges for mirrors. In the current study, the observed mirror FOV, particularly in the left mirror, could have been constrained by mirror adjustment range, although it seems unlikely that such a restriction could have substantially affected the findings.

The findings from the present study are surprisingly similar to those presented by Olson and Winkler 15 years ago. The left-mirror FOV distributions, in particular, are very similar. The similarities to Olson and Winkler's much larger sample provide confidence that the data from the current small sample are reasonably representative of mirror FOV in passenger cars.

The most important limitation of the current work is the restriction to passenger cars. Light trucks, minivans, and sport utility vehicles comprise over half the new vehicles sold in the United States, and their percentage of the vehicle fleet continues to increase. A subsequent study will examine the FOV in such vehicles using similar techniques. Some data not gathered in this study should be included in future investigations of mirror FOV, including the shape of the B-pillar and door opening (which restricts peripheral vision for many drivers), mirror adjustment ranges, and the day/night mirror setting in normal day-time use.

References

Flannagan, C.A.C. and Flannagan, M. J. (1998). *Predicting mirror adjustment range for driver accommodation.* Technical report UMTRI-98-45. University of Michigan Transportation Research Institute, Ann Arbor, MI.

Olson, P.L. and Winkler, C.B. (1985). *Measurement of crash avoidance characteristics of vehicles in use.* Technical report UMTRI-85-20. University of Michigan Transportation Research Institute, Ann Arbor, MI.

Society of Automotive Engineers (1999). *SAE Handbook.* Society of Automotive Engineers, Warrendale, PA.

Appendix A
Participant Interaction Script

This script lists the participant instructions as delivered by the investigators at various stages of testing. For more information on the test procedures, see the Methods section.

Instructions before entering the vehicle for testing:

> "We will make several measures while you are looking into your rearview mirrors. These measures include a few landmarks on your face, as well as some on your vehicle. You will be stepping out of your car a few times so that we may make some measures inside of your vehicle. When you first return to your vehicle please do not touch your mirror locations. We would like to measure the mirrors in the position that you drove here with them today. We will then let you reaim your mirrors after this first measurement and redo similar measurements. We will then have a final questionnaire for you to fill out and take some photos of your car and the mirrors."

Explanation of manual measurement procedures, beginning with vertical field of view:

> "Please sit as if you are driving your vehicle with both hands on the steering wheel. Look into the (left|center|right) mirror as you would during normal driving conditions. We will make an initial setting of the target on this pole and then ask you to tell us where the edges of your field of view are. We would like you to look at the target and tell us when the center of the target is at the edge of your viewing range. This may be at the edge of your mirror, at the edge of your car, or at the edge of a window. Please inform us as to which of these it is. We will begin by asking you to locate an extreme upper and lower position. (Investigator) will move the target up/down the pole; please say stop when it reaches the edge of your viewing range. If we go too far or need to move farther please ask us to move it again. Remember that ideally exactly half of the round target will be visible, that is, the cross hairs between the yellow and black areas will be exactly at the edge of your field of view. Please keep both eyes open at all times. Consider the target visible if you can see it with either eye."

Continuing with lateral field of view:

> "(Investigator) will now move the pole toward the edge of your field of view. Please tell us to stop when the target is at the edge of your viewing range. Once again, if we go too far or need to move further please ask us to move it again."

For the reaiming trials, the following instructions were given:

> “Please reaim your mirrors so that they are in your preferred position for use in normal driving conditions.”

The manual measurement instructions above were repeated for the trials with reaimed mirrors.

Appendix B
Data Form and Questionnaire

Date ____________ Participant number _________________

Name _______________________________ ☐ Male ☐ Female

Birthdate ___________________

Visual Correction: ☐ None ☐ Glasses ☐ Contacts ☐ Refractive surgery

Years of driving experience __________ Annual mileage _____________

Vehicle information:

Make ______________ Model ______________ Year ______________

VIN ______________________________________ across car dist. ___________

Mirror adjustment: ☐ Manual ☐ Power

Anthropometry:

Height (shoes off) __________Weight _____________Seated eye height ___________

Interpupillary _________ Erect sitting height _________Corner eye breadth _________

Center mirror: ☐ Electrochromic ☐ Prism antiglare

☐ Special condition, describe: ______________________________

Left limit ____________ ☐ Mirror edge ☐ Window

Right limit ____________ ☐ Mirror edge ☐ Window

Top limit ____________ ☐ Mirror edge ☐ Window

Bottom limit ____________ ☐ Mirror edge ☐ Window/trunk Edge

Left mirror: ☐ Electrochromic

☐ Special condition, describe: ______________________________

Left limit ____________

Right limit ____________ ☐ Mirror edge ☐ Car body

Top limit ____________

Bottom limit ____________

Right mirror: ☐ Electrochromic

☐ Special condition, describe: ______________________________

Left limit ____________ ☐ Mirror edge ☐ Car body

Right limit ____________

Top limit ____________

Bottom limit ____________

Digital measurements are made also at this time of:

Eye positions looking at each mirror are recorded just after direct measure
Eye positions looking forward
Eye positions looking left (right and left side of head digitized here)

Driver is offered a chance to reaim mirrors. If he/she does reaim, the mirror(s) involved are remeasured:

Center mirror	☐ Not reaimed	☐ Reaimed
Left mirror	☐ Not reaimed	☐ Reaimed
Right mirror	☐ Not reaimed	☐ Reaimed

Center mirror (remeasurement):

Left limit ___________ ☐ Mirror edge ☐ Window

Right limit ___________ ☐ Mirror edge ☐ Window

Top limit ___________ ☐ Mirror edge ☐ Window

Bottom limit ___________ ☐ Mirror edge ☐ Window/trunk Edge

Left mirror (remeasurement):

Left limit ___________

Right limit ___________ ☐ Mirror edge ☐ Car body

Top limit ___________

Bottom limit ___________

Right mirror (remeasurment):

Left limit ___________ ☐ Mirror edge ☐ Car body

Right limit ___________

Top limit ___________

Bottom limit ___________

Debriefing questions:

1. Do you normally use the day/night setting of your inside mirror at night?
2. When was the last time, before just now, you checked the aim of your mirrors?
3. How often do you normally check the aim of your mirrors?
4. Does anyone else regularly drive the car you brought here today?
5. If someone else drives the car, do you have to reaim the mirrors after they use it?
6. Do you have any special strategy for aiming your mirrors?
7. Do you have any special problems with rearview mirror aiming?