Study of Driver Performance/Acceptance Using Aspheric Mirrors in Light Vehicle Applications

Paul S. Rau, Ph.D., **CPE**
National Highway Traffic Safety Administration
Walter W. Wierwille, Ph.D., P.E.
William A. Schaudt, M.S.
Jeremy Spaulding, M.S.
Richard J. Hanowski, Ph.D.
Virginia Tech Transportation Institute
United States
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ABSTRACT

Advances in mirror technology have motivated the need for revisiting the question of how drivers use their mirrors while driving. Blind spots are the common complaint of mirrors, and new designs have appeared in the U.S. and European markets to help improve overall visibility. This research involves the study of how drivers perform and accept various combinations of left and right outside planar, convex, and aspheric mirrors. In addition, this research expands the basic design to examine the effect of increasing the vertical dimension of mirrors. This paper reports the work in progress, including the most recent research issues and activities completed just prior to data analysis.

INTRODUCTION

Research and development on automotive rear-view mirrors has been ongoing for many years and has resulted in numerous technical papers, concepts, recommendations, and patents. Many types of mirrors have been developed, but only a few are in common use in light vehicles today. In recent years, a divergence has occurred between mirrors used in the U.S. and mirrors used in the E.U. While the U.S. has stayed with outside rear-view mirrors that are flat or convex, the E.U. has allowed the outside rear-view mirrors to include so-called "aspherics." Other countries and regions have other requirements, but those requirements do not differ too greatly from those of the U.S. or E.U. Thus, there are mainly three types of outside rear-view mirrors in use today: flat, convex, and aspheric.

A flat (planar) mirror is one in which the mirror surface is a plane (within manufacturing tolerances). A flat mirror has the advantage of preserving object size and apparent distance in the virtual image appearing in the mirror.

A convex mirror has a general definition as well as a specific definition. The general definition is that the surface of the mirror protrudes toward the user, and the specific definition is that the mirror surface is spherical (again, within manufacturing tolerances), that is, it has a constant radius of curvature across the entire surface, regardless of direction. Generally, a convex mirror is considered to be spherical in shape unless otherwise stated. A convex mirror minifies the image, that is, it reduces the angular subtense of the image at the observer's eye but it does not otherwise appreciably distort the image until the radius of curvature becomes very small.

An aspheric mirror also has a general definition and a specific definition. The general definition is that the mirror has a complex contour that is neither flat nor spherical. The specific definition is that the mirror is composed of two parts: a convex (spherical) inner portion; and an outer portion that increases in curvature, horizontally (while the vertical radius remains constant). The two portions are separated by a vertical solid or dashed line that is etched into the mirror. The intent of increasing the horizontal curvature of the outer portion is to increase the field of view of the mirror even though some image distortion may occur.

This research has the objective of evaluating and comparing the various outside rear-view mirrors for use in light vehicles. An important goal is to determine the advantages and disadvantages of aspheric mirrors relative to flat or convex mirrors, and then to make recommendations regarding their use. An important additional goal is to determine any age effects that might be involved in the use of aspheric mirrors with particular emphasis on older driver issues.

PROBLEM SIZE

In 2005, there were approximately 6.16 million property damage and injury crashes. Of these crashes, it is estimated that 4.3 million resulted in property damage only, 1.8 million resulted in injury, and there were 43,443 fatalities (NHTSA, 2005). Of the crashes involving only property damage, 4.3% (298,000) were from merging/lane changing maneuvers and 1.4% (96,000) resulted from passing another vehicle. Of the crashes involving injury, 2.3% (61,000) were from merging/lane changing maneuvers and 0.8% (22,000) resulted from passing another vehicle. Of the fatal crashes, 2% (1008) resulted from merging/lane changing maneuvers and 2.1% (1062) resulted from passing another vehicle. These statistics, taken from Traffic Safety Facts, 2005, were obtained from the Fatality Analysis Reporting System (FARS) and General Estimates System (GES) databases. It is quite possible that a lack of visibility in regard to merging, lane changing, and passing may have been an important factor in many of these crashes.

There is evidence that convex mirrors on the driver's side of European vehicles help to reduce crashes. Luoma, Sivak, and Flannagan (1995) examined lane change crashes, related to exterior mirror type, involving light vehicles in Finland. These crashes were reported to Finnish insurance companies between 1987 and 1992. Results from this study suggested that convex and aspheric mirrors on the driver's side reduced crashes during driver's side lane changes by 22%. These results suggest there is some benefit to having non-planar driver's side mirrors.

Similarly, Schumann, Sivak, and Flannagan (1996) examined whether or not convex mirrors installed on the driver's side were of any value. Crash data were examined using a database containing crashes occurring in Great Britain from 1989 to 1992. The results of the study suggested that having convex mirrors on the driver's side of the vehicle did not increase the likelihood of a crash. In some cases (for example, accidents involving mid-size cars) having convex mirrors on the driver's side of the vehicle reduced the probability of a crash.

In a later study by Luoma, Flannagan and Sivak (2000), different from the previously mentioned 1995 study, lane change crashes and effects from non-planar mirrors were examined. Both spherical convex mirrors and aspheric mirrors were examined in this study. A Finnish crash database was used to find lane change crashes between 1987 and 1998. Results suggest that although there was no statistically significant difference between spherically convex mirrors and aspheric mirrors, when compared to planar mirrors, both types of non-planar mirrors reduced the likelihood of a crash by 22.9%. This study supports the findings of previous studies. Moreover, the results from this study are very similar to results from the previous 1995 study. Based on results from the European studies, it appears that there is a benefit to having convex or aspheric mirrors on the driver's side of the vehicle. However, there is no evidence suggesting that one type is better than the other.

REGULATIONS

Regulations in Europe differ from those in the U.S. regarding rear-view mirrors. The Code of Federal Regulations (§571.111), that is, FMVSS No. 111, requires mirrors on both the driver side and interior of a light vehicle. The standard also specifies the types of passenger side mirrors that may be used. The driver side mirror must be planar (unit magnification). The passenger side mirror can be (spherically) convex, thereby providing the driver with an expanded field-of-view. However, the convex mirror must have the phrase "objects in mirror are closer than they appear" imprinted on it. The U.S. regulations do not specifically disallow aspheric mirrors but the mirrors used must meet the existing regulations at the time of vehicle manufacture. One manufacturer, Saab, is known to have used aspherics in the U.S. The mirror is used on the passenger side, has a convex portion, and has a contiguous outer portion that is aspheric. These mirrors have been used on certain models since approximately 1990. The most recent European Directive regarding vehicular rear-view mirrors is 2003/97/EC, "type-approval of devices for indirect vision and of vehicles equipped with these devices" (European Parliament and Council, 2003). This Directive (which specifically defines an aspheric mirror and its use on vehicles) repeals the previous Directive regarding rear-view mirrors on vehicles (71/27/EEC). Both spherical and aspheric mirrors provide a driver with an expanded field-of-view. Directive 2003/97/EC defines an aspheric surface as having a constant radius of curvature in only one plane. The definition for an aspheric mirror is as follows (European Directive 2003/97/EC, section 1.1.1.9.): 'Aspherical mirror' means a mirror composed of a spherical and an aspherical part, in which the transition of the reflecting surface from the spherical to the aspherical part has to be marked. The curvature of the main axis of the mirror is defined in the x/y coordinate system defined by the radius of the primary spherical curvature with:

$$y = R - (R^2 - x^2)^{1/2} + k(x - a)^3$$

R : nominal radius in the spherical part
k : constant for the change of curvature
a : constant for the spherical size and primary spherical curvature.

The primary purpose of the aspheric mirror is to increase the field of view. The current European Directive allows for aspheric mirrors to be positioned on both the passenger side and the driver side of a light passenger car or light truck. These mirrors must have a clearly visible line dividing the spherical portion and the aspheric portion of the mirror.

The current U.S regulation calls for a unit magnification (planar) mirror on the driver's side and a planar or convex mirror on the passenger side if the inside rearview mirror does not meet certain field of view requirements described in FMVSS 111, section S5.3. The planar mirror on the driver's side must provide a reflected field-of-view that is 2.4 m (7.9 ft) wide at 10.7 m (35.1 ft) behind the eyes of the driver.

If a convex mirror is used on the passenger side of the vehicle, it must have an average radius of curvature between 889 mm and 1,651 mm (35.0 in and 65.0 in). The current European directive (2003/97/EC) is different in that the required fields-of-view for the driver's side and passenger side of a light vehicle are identical. The Directive states that the field-of-view provided by the mirror must be 4 m (13.1 ft) wide at 20 m (65.6 ft) behind the eyes of the driver.

RADIUS OF CURVATURE

The current European Directive (2003/97/EC) indicates that all mirrors must be either spherically convex or planar. A spherically convex mirror may have an aspheric portion on the outer edge of the mirror as long as the rest of the mirror satisfies the required field-of-view.

The radius of curvature of a spherically convex mirror must be measured using a three-point apparatus (two outer points bisected by a middle adjustable point). According to Directive 2003/97/EC, all measurements of radius of curvature must be within 0.85 r and 1.15 r, where r represents the nominal radius of curvature. The radius of curvature of the spherical portion may not be less than 1200 mm (42.2 in) and the radius of curvature of the aspheric portion may not be less than 150 mm (5.9 in). These requirements are in addition to the specification on minimum fields-of view.

HUMAN FACTORS OF ASPHERIC MIRRORS

FIELD OF VIEW

The geometrical fields-of-view differences between images reflected from planar mirrors and images reflected from convex mirrors are described in greater detail in a study by Wierwille, Spaulding, Hanowski, Koepfle, and Olson (2003).

Platzer (1995) indicated that an image produced by a convex mirror is smaller than one produced by a planar mirror. Moreover, the image from a convex mirror appears to increase in size more quickly when moving toward the reflection surface than an image from a planar mirror under the same conditions.

An aspheric mirror currently used in the E.U. contains a spherically convex portion that is roughly two-thirds of the mirror. The outer one-third of the mirror is the aspheric portion that is intended to increase the overall field-of-view.

BLIND SPOT REDUCTION

Although the use of exterior rear-view mirrors increases the driver's field-of-view, there still exists a blind zone for mirrors in the U.S. Platzer (1995) addressed the blind zone around the vehicle and discussed remedial strategies. One noteworthy strategy was a concept developed by Volvo in 1979 and later published by Pilhall (1981). This strategy employed the use of a mirror with a decreasing radius of curvature on the outer one-third of the mirror, that is, an aspheric. Because the use of a convex mirror is permitted in the U.S. on the passenger side, the blind zone on the passenger's side is smaller than the one produced on the driver's side. The blind zone produced on the driver's side is large enough to conceal a vehicle in certain positions (Flannagan, Sivak, & Traube, 1999; Platzer, 1995).

According to Flannagan et al. (1999), a driver's direct peripheral field-of-view has a maximum limit of 180 deg when glancing into the exterior driver's side rear-view mirror. During the glance, the driver can see to the rear on the left side, as a result of this 180 deg field-of-view.

Even though the driver's head is turned, the peripheral field-of-view, in addition to the field-of view produced from the mirror, still leaves a blind zone large enough to hide a vehicle.

Flannagan et al. (1999) also indicated that the 180 deg limit was probably smaller for older drivers, thereby resulting in an even larger blind zone. If the field-of-view of the driver's mirror could be expanded to cover 45 deg, then the blind spot would essentially be eliminated provided the driver's peripheral field-of-view was sufficiently useful. The deleterious consequences of using a convex or aspheric mirror on the driver's side would need to be explored, because the image in the mirror is then "minified" by the mirror.

DISTANCE PERCEPTION

Because an aspheric mirror is a convex mirror (in the general sense), the reflected image is changed in terms of size and apparent distance. As the radius of curvature decreases, the image becomes increasingly changed. The apparent size of an object decreases as the radius of curvature decreases, making it appear increasingly farther away. Since convex mirrors change an image, there have been numerous studies examining distance perception using convex rear-view mirrors versus planar mirrors (Flannagan Sivak & Traube, 1997; Flannagan, Sivak, Schumann, Kojima, & Traube, 1997; Flannagan, Sivak, & Traube, 1996; Mortimer & Jorgeson, 1974; O'Day, 1998; Walraven & Michon, 1969). Research has indicated that distance judgments made with planar mirrors are different from estimates made with convex mirrors. On average, drivers will underestimate distance when using flat mirrors. Underestimation is a desirable attribute because it does not increase the likelihood of a collision, i.e., the driver thinks the vehicle is closer than it actually is, and therefore, there is more clearance than is perceived. When drivers estimate distance using convex mirrors, the average underestimation of distance is reduced or eliminated. Since this is an average value, many of the samples will actually involve distance overestimation which can be dangerous. In this case, clearances would be smaller than the driver perceives them to be. Many of the research studies listed above do not explicitly state these general findings, even though the data in the research studies do, in fact, clearly support them.

In research regarding distance perception of large-radius convex mirrors, Flannagan, Sivak, and Traube (1998) concluded that, as the radius of curvature of a convex mirror increased (curvature decreased), the overestimation of distance (as compared with flat mirrors) decreased. However, even the largest radius of curvature (8,900 mm) resulted in a non-dismissible distance overestimation of approximately 8%. Again, this is an over-estimation as compared with the under-estimation that occurs with flat mirrors.

ADAPTATION

Research by Flannagan, Sivak, and Traube (1996) examined adaptation to aspheric mirrors and distance judgments accompanying increased use. The results suggested that increased use of aspheric mirrors decreased distance over-estimation, indicating that drivers adapted to the aspheric mirrors. However, the decrease in distance over-estimation was never as low as that of the planar mirror. This could imply that over-estimation of distance (compared with flat mirrors) will exist for all drivers regardless of how well drivers adapt to the aspheric mirrors.

BINOCULAR DISPARITY

Research by O'Day (1998) suggests that binocular disparity is relatively unaffected by object distance in an aspheric mirror. O'Day used analytical techniques to determine the type of test that should be used to assess binocular disparity. However, his paper does not include tests with actual driver/participants. Consequently, questions with regard to binocular disparity remain unanswered at this time. In O'Day's words,

"It remains to be determined how much disparity is tolerable…, and when the image disparity becomes bothersome. The level of image disparity that causes the driver to see double images needs to be determined".

DISTORTION

It should be recognized that the outer (aspheric) portion of the mirror would be used almost exclusively for presence/absence detection. Consequently, it appears that even though there may be substantial distortions, the mirror can still be used for its primary purpose, namely, object detection. All of the previous research shows similar results. Distance is consistently over-estimated in convex mirrors (as compared with flat mirrors, for which underestimation is the rule). This includes both spherically convex and aspheric mirrors. Flanagan, Sivak, & Traube (1997) provide a summary of previous findings.

RESPONSE TIME AND GAP ACCEPTANCE

There is a trade-off between planar and convex rear-view mirrors. Planar mirrors are believed to provide a driver with accurate (and possibly conservative) distance and speed information but with a relatively small field-of-view. A convex mirror provides a driver with a larger field-of view but with somewhat inaccurate distance and speed information. Which is the better choice for the mirror on the driver's side of the vehicle? One argument in favor of convex mirrors, and also aspheric mirrors, could be response time for object detection.

Helmers, Flannagan, Sivak, Owens, Battle, and Sato (1992) found that responses for object detection were fastest when using an aspheric mirror. Planar, spherically convex, and aspheric mirrors were used in the study to determine object detection time. The planar mirror had the longest detection time. This was in part due to head movements that many drivers use to compensate for the smaller field-of-view. Because the aspheric mirror had a larger field-of-view, object detection took less time. The planar mirror resulted in the slowest average response time (1,676 ms) while the aspheric mirror resulted in the fastest average response time (1,316 ms).

Mortimer (1971) conducted research on lane changing/passing performance of drivers. This study showed that during lane changing maneuvers, gap acceptance judgments were essentially the same for both planar and convex rear-view mirrors, provided that a planar interior rear-view mirror was present. It should be noted that when only exterior rear-view mirrors were used (no interior mirror), gaps judged acceptable were smaller with convex mirrors than with planar mirrors. Also, it was found that in making lane changes, convex mirrors were not viewed more often or longer than planar mirrors during gap judgments. Although this study did not incorporate aspheric mirrors, it does show that when either a planar or convex exterior mirror was coupled with a planar interior rear-view mirror, gap judgments did not significantly differ between the two mirror types. It may be the case that aspheric mirrors result in similar gap acceptance judgments as well. Other studies, such as Mortimer and Jorgeson (1974) and Walraven and Michon (1969), show similar results regarding gap acceptance judgments for lane changing and passing tasks. In the study by Mortimer and Jorgeson (1974) it should be noted that a planar interior mirror was always used in combination with a convex mirror.

A further experiment by de Vos, Van der Horst, & Perel, 2001; de Vos, 2000 examined gap acceptance with planar, spherically convex mirrors, and aspheric mirrors. Using a "last safe gap" method where a car approached from behind in the adjacent lane at a constant speed, the participant was to determine at what point it was no longer safe to change lanes. Also, the participant had to determine the approximate position of the approaching vehicle in the lane adjacent to the driver's side. Results from this part of the study were consistent with those of previous studies. Gaps deemed acceptable for lane changing were larger for planar mirrors than for convex mirrors. Gaps considered acceptable for lane changing via aspheric mirror (with a radius of curvature = 2,000 mm, 6.56 ft) fell between those for planar mirrors and spherically convex mirrors.

According to de Vos (2000), the experiment employed a "worst case scenario" meaning only exterior rear-view mirrors were allowed. This procedure replicated occurrences where interior mirrors may not be available or their field-of-view would be blocked. Future research should examine gap acceptance and detection using planar, spherically convex, or aspheric exterior mirrors used in combination with a planar interior mirror. Acceptable gap information derived from such an experiment may be different from that resulting from using exterior mirrors alone.

EUROPEAN DRIVERS

Research by de Vos (2000) and de Vos, Theeuwes, and Perel (2001) examined European driver experience and knowledge of rear-view mirrors via surveys of mirror types and use. Findings from the studies suggest that drivers are very receptive to having aspheric mirrors on the driver's side of the vehicle. However, one result of the survey was that 46% of the participants did not know that the image produced in a non-planar mirror is modified. Of these respondents, 15% thought that the image is magnified rather than minified. Interestingly, drivers responded similarly for planar versus aspheric mirrors when asked of their ability to judge approach speed of vehicles using the mirror. Overall, the majority of drivers expressed a preference for a nonplanar mirror on the driver's side of the vehicle. Drivers stated that they would choose an aspheric mirror if given the option.

OLDER AND YOUNGER DRIVER DIFFERENCES

Another condition studied by de Vos (2000) was the difference between older drivers and younger drivers. Overall, drivers accepted smaller gaps with convex mirrors than with planar mirrors. This appears to be a result of the minification of the image produced by the convex mirror. Another finding was that older drivers tended to be more conservative than younger drivers, meaning that they tended to wait for larger gaps before deeming them acceptable. The number of glances to the mirror was similar for both older and younger drivers. However, older drivers made more detection mistakes than younger drivers when using the convex mirrors. The opposite was true for detection using planar mirrors, that is, younger drivers made more detection mistakes with planar mirrors.

ACCEPTANCE OF ASPHERIC MIRRORS

If aspheric mirrors were permitted on U.S. vehicles, would these mirrors be accepted by drivers? Research by Flannagan and Flannagan (1998) showed that non-planar mirrors were initially preferred over planar mirrors on the driver's side of the vehicle. This preference for non-planar mirrors also increased after four weeks of use. The study was performed using 114 employees from the Ford Motor Company with either one of two spherically convex mirrors or with one of three aspheric mirrors in place of the planar driver's side mirror. The aspheric mirrors varied in terms of the size of the aspheric portion of the mirror (34%, 40%, and 66%).

Findings from the research suggested that the convex and aspheric mirrors were generally preferred over planar mirrors. The only mirror not as strongly supported was an aspheric mirror with an aspheric portion that was 66% of the mirror surface. Findings from this study, although not exactly representative of the U.S. driver population (because participants were better informed on automotive-related issues than the average driver), may suggest that aspheric mirrors would generally be accepted and would likely increase in acceptance over time. There is a second indication of acceptance; since these mirrors are currently used on the driver's side of many European light vehicles, the acceptability and preference for them is probably satisfactory.

EXPERIMENT

The experiments described herein had two important objectives: assessment of driver acceptance of aspherics and evaluation of gap acceptance for aspherics relative to other types of mirrors that could be used. Since aspherics could be used on the driver's side or the passenger's side, both sides were examined. (There has been very little dynamic testing done on passenger's side aspherics.) Although this paper specifically reports on the dynamic testing only, it is important to note that many other research activities were undertaken in this project including a comprehensive literature review of aspherics in light vehicles, optical and mathematical analyses, and static experimentation.

Information on subjective acceptance was obtained using rating scales associated with two aspects of coordination (with the conventional interior rear view mirror). One of these aspects was "Coordination" and the other was "Speed and Distance Estimation". Four other aspects associated with the given outside rearview mirror itself. These four were "Field of View of the Outside Mirror (by itself)", "Distortion", "Uneasiness", and "Comfort Level". The six aspects taken together should provide an overall assessment of acceptance.

Gap acceptance was obtained for each mirror using the "last safe gap" technique (referred to in this experiment as the last comfortable gap). Last comfortable gap was defined as follows for each subject: Last comfortable gap is the last point where you would feel comfortable changing lanes (with moderate acceleration) to safely move into the lane of the overtaking vehicle. Using a closing speed of 10mph (16.1 km/h), drivers pressed a button at the last instant they deemed it is still safe to accelerate and change lanes in front of an oncoming vehicle. Gap acceptance was also determined by way of one passing and two merging maneuvers. There is the possibility that gap acceptance may be shortened with aspheric mirrors. If so, the magnitude of this shortening needs to be assessed.

MIRRORS INCLUDED IN THE EXPERIMENT

Mirrors included in the road tests were chosen on the basis of several factors. The mirror complement included aspherics that were typical candidates, so that they could be evaluated. In addition, other types of mirrors were also included for comparison purposes.

The driver's side was considered separate from the passenger's side. There are two reasons for this: a given mirror will provide different fields of view depending on the side of the vehicle on which it is installed (Wierwille, Spaulding, and Hanowski, 2005). This is a result of the difference in distance from the mirror to the driver's eyes for the two sides of the vehicle. Also, current U.S. regulations differ for the driver's side and passenger's side mirrors. Consequently, mirrors selected as baselines differed for the two sides of the vehicle. It is important to note that the interior rear-view mirror was made available to all drivers to use in combination with all exterior rear-view mirrors in this experiment.

DRIVER'S SIDE MIRRORS TESTED

Current U.S. regulations require a flat (planar) mirror on the driver's side of the vehicle. Researchers have concentrated on this side in the belief that alternative mirrors would be preferable. In particular, it is widely believed that the advantage of the unit magnification feature of flat mirrors is not as important as the disadvantage of limited field of view. The blind spot created by flat mirrors is believed to create greater risk for the driver. In any case, since a flat mirror is currently required by the regulations, the F-D (flat, driver's side) mirror case was included as the baseline test mirror.

One form of competing alternative is a convex mirror. This mirror has a greater field of view and less nighttime glare. However, it produces some image minification. There are two representative possible alternatives: C20-D and C14-D. The C20-D alternative has a radius of curvature of 2000 mm, producing mild minification and almost twice the field of view of approximately 22.6 degrees. Nevertheless, a substantial blind spot remains. This mirror represents a compromise, having some blind spot reduction and mild minification. The C14-D has a larger field of view of approximately 28.4 degrees and greater minification. This mirror also represents a viable compromise, but still has a blind spot. The two mirrors were considered to be possible alternatives to the flat mirror. They were therefore included in the testing.

Similarly, two aspheric mirrors were included for testing on the driver side. The primary reason for studying aspherics is that they are believed to increase the likelihood of object detection by providing a wide field of view. This can be accomplished with the A20-D aspheric or the A14-D aspheric. The A20-D aspheric has a slightly larger aspheric region than the A14-D, but less minification than the A14-D. Both mirrors represent viable alternatives with large fields of view.

Two additional mirrors were included in the testing for the driver side. Recently, a research study reported that foreground was important in estimating distance to objects (Wu, Ooi, and He, 2004). The gist of the study was that under monocular viewing conditions and uniform field, and when foreground was available to human subjects, they could do a better job of estimating distance to objects. This finding may have ramifications for rearview mirror design for light vehicles. If the mirrors are elongated, they might allow better distance estimation, which in turn could affect gap acceptance as well as understanding of traffic situations. Consequently, two additional new mirrors were tested on the driver side: a flat, elongated mirror designated F-Elongated-D and a convex, elongated mirror designated C14-Elongated-D (with 1400 mm radius of curvature). The mirrors were cut from large van mirrors to fit the research vehicle. It was necessary to cut the lower right corner of each mirror diagonally so that it would not come in contact with the driver's door. The mirrors had dimensions that allowed their entire mirror surfaces to be viewable from the driver's seat, that is, overall, 22.4 cm (8.8 in) high by 15.5 cm (6.1 in) wide. The mirrors combined with a light-weight spacer were attached over the original equipment mirror using hook and loop tape (as was the case for all of the mirrors).

The elongated mirrors provided a view of the pavement closer to the vehicle. In other words, when compared with all of the other mirrors, the driver had a view corresponding to the usual F-D or C14-D mirror, plus a portion of the foreground of this view. Therefore, in total, seven mirrors were tested on the driver side of the vehicle. The mirrors provided exemplars of the various classes, (flat, convex, aspheric, and elongated), thereby allowing direct comparisons across mirror types and characteristics.

PASSENGER'S SIDE MIRRORS TESTED

Current regulations allow for a flat or a convex mirror to be used on the passenger's side. However, industry practice has been to provide convex mirrors on the passenger's side of new light vehicles. Consequently, there are no known new light vehicles with flat mirrors on the passenger's side. The regulations require that if a convex mirror is used, it must have a radius of curvature between 889 and 1651 mm. A brief examination of 60 vehicles in a typical parking lot showed that the mirrors had radii of curvature between 970 to 1460 mm, a range that is clearly inside the current regulations.

Realistically, the baseline mirror should be convex and it should have a radius of curvature within the range actually encountered. The C14-P mirror that was previously tested meets these requirements. Its 1400 mm radius of curvature falls within the range actually used on vehicles. The mirror produces a one-eyed field of view of approximately 21 degrees with good nighttime glare attenuation, but with substantial image minification.

Many vehicles currently have convex mirrors with radii of curvature around 1000 mm. These mirrors meet current U.S. standards, as expected, and are probably used to increase the field of view on the passenger side. Because of these circumstances, it was decided to test such a mirror. To do so, a multi-step process was used. First, a vehicle was found that had a large convex mirror with a radius of curvature close to 1000 mm. Duplicate factory original mirrors were then ordered. The new mirrors were then removed from their backings using a solvent, and finally they were cut to the correct profile using a water-jet machining process. This produced mirrors designated as C10-P that could be used for the experiment.

There were two possible alternative aspheric mirrors for the passenger's side, the A14-P and the A20-P. Both mirrors provide a one-eyed field of view of approximately 35 degrees, and both provide substantial glare reduction in nighttime driving. The A14-P mirror has a convex portion with a radius of curvature of 1400 mm, thus meeting the current standard. In fact, the 1999 to 2001 Saab 9-5 actually uses this mirror, but apparently is unique among cars sold in the U.S.

The A20-P has less curvature in its convex portion, that is, 2000 mm of radius. The A20-P has approximately the same overall field of view as the A14-P, but less image minification in its convex portion. Therefore, it may have a possible advantage in that objects appear a bit larger. The A20-P has a larger aspheric region than the A14-P, so that the total field of view is about the same as the A14-P. Since both aspheric mirrors were considered to be viable candidates, both were included in the road testing. Note that a C20-P was not included on the passenger's side for testing. The reason for this is that it does not seem to have the necessary field of view when used on the passenger's side, and it also falls outside U.S. current regulations. Since drivers now use mirrors with radii of curvature between 889 and 1651 mm and the corresponding fields of view created by them, it seemed undesirable and unnecessary to test such a mirror, which has less curvature.

To account for elongation, one additional mirror was tested. It was designated as a C14-Elongated-P. This mirror had an almost square shape. It did not have as much length as the C14-Elongated-D, because the passenger-side door prevented viewing of the lower portion by the driver. Thus, the mirror was cut to be longer, but it did not extend so far down that the line of sight from the driver's position was obstructed in the lower part. It was deemed undesirable to test a mirror as long as the C14-Elongated-D because such a design would have required complete redesign of the passenger side door in future vehicles. No doubt, such an approach would meet with stiff resistance. The C14-Elongated-P had dimensions that allowed its entire mirror surface to be viewable from the driver's seat, that is, 16.1 cm (6.3 in) high by 17.9 cm (7.05 in) wide. It used a spacer similar to that used for the C14-Elongated-D and the F-Elongated-D, so that the mirror could be aimed using the controls inside the research vehicle.

Similarly, since flat mirrors are no longer used on the passenger's side of light vehicles, and since they have a narrow field of view, they are not viable candidates for modern light vehicles. Thus, the five mirrors selected for testing on the passenger side were the C14-P, the C10-P, the A14-P, the A20-P, and the C14-Elongated-P. These mirrors were believed to represent the most viable candidates for the passenger side of the vehicle.

DESCRIPTION OF MIRRORS

The following descriptions of mirrors were provided to subjects.

<u>Driver's Side</u>

F-D

This mirror has a flat surface. It is like the one you currently have on the driver's side of your own vehicle. Objects seen in this mirror are the same size as when they are seen directly.

This is like a typical mirror in your own home. If you look into it, all objects are correctly sized in the reflection. The field of view of this mirror is relatively narrow. It's possible to miss an object on the driver's side because of the narrow field of view.

C20-D
This mirror has a slightly convex (or spherical) surface. The purpose is to give a somewhat wider field of view than a flat mirror, so there is less chance of missing an object on the driver's side of the vehicle. However, this mirror also makes objects look a little smaller than they really are. If you look into it, all objects are a little smaller, so the scene looks correct but is smaller.

C14-D
This mirror has slightly more curvature than the C20-D mirror. The purpose is to give a wider field of view than a flat mirror (and an even wider field of view than the C20-D mirror), so there is less chance of missing an object on the driver's side of the vehicle. However, this mirror also makes objects look a little smaller than they really are. If you look into it, all objects are a little smaller, so the scene looks correct but is smaller (this mirror makes objects look even smaller than they appear in the C20-D mirror).

A20-D
This mirror has two parts: an inner part that has a slightly convex (or spherical) surface, and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so that there is very little chance of missing an object on the driver's side of the vehicle. However, when looking into the inner (convex) part of this mirror, objects look a little smaller than they really are. Also, when looking into the outer part, objects appear smaller and a little squeezed.

A14-D
This mirror has two parts, just like the A20-D mirror. The two parts are an inner convex portion and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so that there is very little chance of missing an object on the driver's side of the vehicle. This mirror is slightly different than the A20-D mirror. The inner portion is curved more, making objects appear a little smaller. The outer curved portion of the mirror is slightly narrower than the outer portion on the A20-D mirror. As with the A20-D, when looking into the outer part, objects appear smaller and a little squeezed.

F-Elongated-D
This mirror has a flat surface. It is like the one you currently have on the driver's side of your own vehicle, except that it is longer vertically. Objects seen in this mirror are the same size as when they are seen directly. This is like a typical mirror in your own home. If you look into it, all objects are correctly sized in the reflection. This mirror provides a more elongated field of view than a conventional flat mirror for this vehicle. The purpose of this is to provide a view of the ground closer to you, which may help in estimating distances to other objects viewed in the mirror.

C14-Elongated-D
The purpose is to give a wider field of view than a flat mirror, so there is less chance of missing an object on the driver's side of the vehicle. It has the same curvature and viewing effect that the smaller C14-D mirror has, but this one is longer vertically. Its purpose is to provide an elongated viewing area. Just like the F-Elongated-D mirror, the purpose of this mirror is to provide a view of the ground closer to you, which may help in estimating distances to other objects viewed in the mirror. However, because this mirror is slightly convex, it will make objects appear slightly smaller than they actually are.

Passenger's Side

C14-P
This mirror has a convex (or spherical) surface. It is like the one you currently have on the passenger's side of your own vehicle. The mirror is convex to increase the field of view (as compared with a flat mirror), so there is less chance of missing an object on the passenger's side of the vehicle. However, this mirror also makes objects look smaller than they really are, and it is still possible to miss an object occasionally. If you look into it, all objects are smaller.

C10-P
This mirror has slightly more curvature than the C14-P mirror. The purpose is to give a wider field of view than the C14-P mirror, so there is less chance of missing an object on the passenger's side of the vehicle. However, this mirror also makes objects look a little smaller than they really are. If you look into it, all objects are a little smaller, so the scene looks correct but is smaller (this mirror makes objects look even smaller than they appear in the C14-P mirror).

A20-P
This mirror has two parts: an inner part that has a slightly convex (or spherical) surface, and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so there is very little chance of missing an object on the passenger's side of the vehicle. However, when looking into the inner (convex) part of the mirror, objects appear a little smaller. Also, when looking into the outer part, objects appear a little smaller and a little squeezed. (Objects in this

mirror appear slightly larger than in the A14-P mirror.)

A14-P
This mirror has two parts: an inner part that has a convex (or spherical) surface, and an outer part that is curved outward. The two parts are separated by a vertical line. The purpose of this mirror is to provide a wide field of view so there is very little chance of missing an object on the passenger's side of the vehicle. However, when looking into the inner (convex) part of the mirror, objects look smaller than they really are. Also, when looking into the outer part, objects appear smaller and a little squeezed. (Objects in this mirror appear slightly smaller than in the A20-P mirror.)

C14-Elongated-P
This mirror has a convex (or spherical) surface. It is like the one you currently have on the passenger's side of your own vehicle. It has the same curvature and viewing effect that the smaller C14-P mirror has, but this one is elongated. The purpose of this mirror is to provide a view of the ground closer to you, which may help in estimating distances to other objects viewed in the mirror. However, because this mirror is slightly convex, it will make objects appear slightly smaller than they actually are.

EXPERIMENTAL DESIGN AND INDEPENDENT VARIABLES

This experiment used 28 subjects for the driver side mirrors and another 20 (different) subjects for the passenger side mirrors. Half of the subjects in each experiment were in the younger age group (younger than 35 years) and the other half were in the older age group (older than 64 years). Within each age group and experiment (side), half the subjects were male and half were female. Thus, the experimental design on the driver side was 2 (age groups) by 2 (genders) by 7 (mirrors) with 7 drivers in each age-gender group. Similarly, the experimental design for the passenger side was 2 (age groups) by 2 (genders) by 5 (mirrors) with 5 drivers in each age-gender group. The mirror variable was the only within-subject variable (for each side of the vehicle).

Runs were counterbalanced, with exact counterbalance correspondence for age and very similar counterbalance for gender. Specifically, for every younger subject there was an older subject with exactly the same order of presentation. On the driver side, the first set of seven younger subjects received exactly the same set of counterbalanced orders as the first seven older subjects. The second set of seven younger subjects used a different set of counterbalanced orders, and the second set of older subjects received this same second set of counterbalanced orders.

For the passenger side, an identical procedure was used. There were, similarly, two sets of counterbalanced orders for five mirrors. The first five younger subjects received the first set of counterbalanced orders, and the second group of five younger subjects received the second (different) set of counterbalanced orders. There was a corresponding older subject for each younger subject.

INSTRUMENTATION

All tests were performed on the Virginia Smart Road in Blacksburg, VA. This is a 2.2 mile (3.5km) long (each direction) instrumented road with a large size turnaround loop at one end and a moderate size turnaround loop at the other end. It is used for research and test purposes, and is closed to the public.

The main instrumentation for this experiment was installed in the experimental vehicle. It included a four-camera video recording system with insert-keyed test condition information, a DGPS distance measuring system, a pushbutton on the right stalk just behind the right side of the steering wheel, and a data acquisition system with an interface to store data as they were gathered.

The twelve test mirrors were prepared. They had any protruding rear components machined away, and they were attached using hook and loop tape over the experimental vehicle's original mirrors in exactly the same way as the previous, static experiments. Elongated mirrors described earlier used a light-weight spacer between the back of the mirror and the attaching tape to allow for the larger mirrors to fit in the smaller mirror housings of the vehicle. Changeover by the experimenter and aiming by the subject was generally accomplished in approximately three minutes.

The camera system served two purposes: to gather eye glance information and to serve as backup in case there was any malfunction of the DGPS distance measuring system. One camera was directed toward the driver's face to pick up glance direction. Two cameras were mounted on the rear package shelf and picked up the image of the confederate vehicle in the adjacent lane. One camera aimed into the driver's side adjacent lane and the other aimed into the passenger's side adjacent lane. The fourth camera was aimed forward and was used to provide a geographic reference to position on the Smart Road in case it was needed. The camera was located in front of the interior rear view mirror, out of the view of the subject. The four camera images were combined using a quad splitter.

The DGPS distance measuring system included an antenna mounted at the top center of the trunk of the subject vehicle. A similar antenna and support system were installed in one of the confederate vehicles. Measurements were initially calculated as distances between the two antenna positions. Corrections were then made for bumper to bumper distances. In all cases, bumper to bumper distances were calculated based on projections to the same lane. In other words, the longitudinal gap was calculated. This was accomplished using the coordinates of the two vehicles (for which gap was calculated), along with the azimuth of the confederate vehicle. Correction was made for longitudinal slope of the Smart Road as well.

Coordination of the three vehicles involved in the experiment was accomplished by voice radio communications with the experimenter in the experimental vehicle serving as the run coordinator (that is, the lead experimenter). The two confederate vehicle drivers were carefully trained ahead of time and were given instructions on the ordering of closing speeds and on the appropriate lanes in which to drive. They were also trained in avoidance maneuvers, in case the subject merged without sufficient clearance. In general, the instrumentation was designed to be unobtrusive. Thus, the driving environment appeared relatively natural to the subject.

DEPENDENT VARIABLES

Both objective and subjective measures were obtained from the experiment. The objective measures were associated with performance of the various tasks. Distances at time of pass or merge initiation and distances at button presses (for last comfortable gap) were analyzed. For each mirror, there were two replications of the pass maneuver and two replications of each of the two merge maneuvers. There were eight replications for the last comfortable gap maneuver. In all cases, units of distance were used for the gaps.

Additional analyses were performed on eye glance behavior during the interval just prior to the passing and merging maneuvers and just prior to button presses. These analyses were intended to indicate the degree to which subjects relied on their interior mirrors and the degree to which they relied on their corresponding outside rear view mirrors, for each of the outside mirrors. In other words, eye-scanning differences among the mirrors were examined. In all cases the interval of 10 seconds just prior to initiation of pass or merge or button press was used for analysis. The reasoning here was that this was the interval during which the driver would be determining whether or not it was safe to perform the maneuver.

The subjective ratings were associated with acceptance of each type of mirror tested. As indicated earlier six ratings were obtained, two involving coordination of the given outside mirror with the interior mirror and four involving only the outside mirror. The last item in the ratings was a questionnaire, which allowed drivers to provide any additional information or suggestions they wished to share. The information and suggestion responses were collected and examined for consensus.

Each rating scale had five descriptor levels and nine vertical delineators. The subject was told to circle one and only one of the vertical delineators, or the line at the halfway point between the vertical delineators. This allowed 17 possible scoring positions for each rating. The ratings were analyzed for differences by statistical tests. Each of the six rating dimensions was analyzed separately as a function of mirror type, age, and gender. The six dimensions, taken as a group were intended to provide a general impression of driver acceptance for each type of mirror, as well as specific elements associated with that mirror. Since there were baseline mirrors for each side of the vehicle, the alternatives could be examined relative to these the baselines.

SUBJECT INSTRUCTIONS AND PROCEDURES

Upon arrival, the subject read and signed an informed consent form, assuming that the subject agreed to participate. The informed consent form provided a general description of the experiment and the subject's duties, the level of risk and discomfort, the length of time he or she would participate, and the compensation to be received. Then, the subject was shown duplicates of the mirrors that would be used on the vehicle. Each mirror was explained to the subject, using the same level of explanation, but pointing out the differences and why the mirrors had been selected for experimentation. The mirrors were described in non-technical terms (see Description of Mirrors section).

It was considered important in these explanations to provide general information on each mirror so that the subjects were informed, but to avoid expressing any opinions as to how well the mirrors might perform. The explanations were deemed necessary, because otherwise, subjects would not have been able to accurately evaluate how well the mirrors performed (all the mirrors had a flat appearance).

The ratings form was also shown and explained to the subject. Showing the form ahead of time gave the subject an indication of what duties he or she would have. Similarly, the passing, merging, and last comfortable gap tasks were explained. The definition of "last comfortable gap" was read to each subject. The experimenter and the subject discussed last comfortable gap until it was clear that the subject fully understood the concept.

After the experimenter answered any other questions, the subject sat in the research vehicle and adjusted the seat and interior rear view mirror. Thereafter, the subject drove to the beginning point for the practice loop on the Smart Road. There, the first outside rear view mirror was attached by the experimenter and aimed by the subject using instructions provided by the experimenter. These instructions included aligning the inside edge of the field of view so that the rear door handle, which was the most extreme lateral protrusion on the vehicle could just be seen at the edge of view. The experimenter then again read the description of the specific mirror being used to the subject. The experimenter then explained the passing and two merging maneuvers that would be performed, indicating that the nominal speed of the confederate vehicles would be 30 mph (48.3 km/h). Basically, the subject accelerated the subject vehicle to pass the two confederate vehicles as the vehicles maneuvered toward adjacent lanes from the near-end loop of the Smart Road. The maneuver was intended to provide a realistic passing scenario in which the mirrors would most likely be used. The first merging followed shortly after in which the subject vehicle was initially ahead of the two confederate vehicles. The subject vehicle then decelerated and merged between the two confederate vehicles, which were again traveling at 30 mph (48.3 km/h). For the second merging scenario, the subject vehicle was initially behind the confederate vehicles in the adjacent lane. The subject vehicle then accelerated and merged between the two confederate vehicles, which were again traveling at 30 mph (48.3 km/h). These two scenarios were intended to exercise the use of the rear view mirrors in typical merging situations. When the end of the outbound leg was reached, the vehicles stopped and then repositioned themselves prior to beginning the inbound leg. The subject was also instructed to use the outside rear view mirror and the interior mirror in performing the maneuvers. It was explained that the first loop was a practice loop. Thereafter, the initial outbound leg commenced.

At the end of the outbound leg, the various vehicles took their correct positions for the inbound leg and initially remained standing. While standing, the subject was told to follow the lead vehicle (which would be traveling at a speed of 30 mph, 48.3 km/h) at the calibration distance of 125 ft (38.1 m) as demonstrated by the standing distance. Note that there were two confederate vehicles. On the inbound leg, one was 125 ft (38.1m) in front of th subject vehicle and served as the lead vehicle in car following. The second confederate vehicle approached in the adjacent lane from the rear and served as the overtaking vehicle. The subject was then instructed to press the stalk button at the last comfortable gap and to use the given outside mirror (in combination with the interior mirror) to assess the last comfortable gap, and that there would be four replications, that is, that the confederate vehicle would approach four times during the inbound leg. When the inbound leg was completed, the vehicles took their positions for the next outbound leg.

At the beginning of the second loop the subject was told that data taking would begin, and except for mirror aiming, the same procedures would be used. Once performance data had been gathered for two loops (end of the third loop for the subject), the subject vehicle stopped and the subject provided ratings for the given mirror. Thereafter, the mirror was changed and the process repeated. Note once again that there was only one practice run and it was at the beginning of experiment (first mirror) for each subject. Thus, all runs had two full loops for data gathering, but only the first run had an additional initial practice loop. Counterbalancing insured that each mirror received the same amount of practice across subjects.

ANALYSIS PLAN

The ratings and performance data will be analyzed by parametric tests and also by nonparametric tests where appropriate. Each of the six rating dimensions will be analyzed separately as a function of mirror type, age, and gender using parametric tests. The six dimensions, taken as a group, will provide a general impression of driver acceptance for each type of mirror, as well as specific elements associated with that mirror. Since there is one baseline mirror for each side of the vehicle, the alternatives will be examined relative to these two mirrors. Performance data will be analyzed in terms of changes in gap. Eyeglance analyses will be used to determine information gathering sources the drivers are using.

CONCLUSIONS

This experiment was set up to provide the data necessary to answer important remaining questions in regard to candidate outside rear view mirrors. In the way of review, these are:

1. Which mirrors, if any, create reductions in gap (clearance) during passing and merging maneuvers, as compared with the mirrors now in general use?
2. Which mirrors, if any, create reductions in last comfortable gap for vehicles approaching from the rear in adjacent lanes?
3. Are there changes in driver visual scan patterns associated with candidate outside rear view mirrors, and if so, what are the implications?
4. What is the degree of initial acceptance (based on six different rating dimensions) of the aspheric mirrors relative to current U.S. mirrors?
5. Which mirrors, if any, from the driver's standpoint are preferred?
6. Does Age affect the performance, eyeglance behavior, or ratings as a function of mirror type?

This experiment was set up to answer these questions using a near-operational, realistic, and safe environment. Test conditions were chosen to exercise the mirrors at the places where they were considered to be most critical. The results of the experiment, combined with the earlier information gathering, analysis, and static tests, should provide the necessary background for making recommendations.

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