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

# Final Report

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## ABBREVIATIONS AND NOMENCLATURE

**1AM, 2AM**: first and second (respectively) accelerating merges performed by the subject vehicle

**1P, 2P**: the first and second (respectively) passing maneuvers performed by the subject vehicle

**1DM, 2DM**: first and second (respectively) decelerating merges performed by the subject vehicle

field-of-view**A14**: an aspheric mirror with a convex inner portion having a nominal 1,400 mm radius of curvature

**A14-D**: an A14 mirror used, or to be used, on the driver side of the vehicle

**A14-P**: an A14 mirror used, or to be used, on the passenger side of the vehicle

**α**: criterion level for statistical significance, set to 0.05 throughout all analyses in this report

**ANOVA**: analysis of variance (a statistical analysis technique)

**aspheric mirror**: a rear-view mirror having an aspheric outer portion

**aspheric (outer) portion, aspheric region, aspheric part**: the outer part of an aspheric mirror that uses increasing horizontal curvature to help capture a larger field-of-view

**aspheric**: short name for an aspheric mirror

**C14**: a convex mirror having a nominal 1,400 mm radius of curvature

**C14-D**: a C14 mirror used, to be used, on the driver side of the vehicle

**C14-P**: a C14 mirror used, to be used, on the passenger side of the vehicle

**C14-E; C14-Elongated**: a convex mirror that is longer than the C14 vertically and has a nominal 1,400 mm radius of curvature throughout

**C14-Elongated-D**: a C14-E mirror used, or to be used, on the driver side of the vehicle

**C14-Elongated-P**: a C14-E mirror used, or to be used, on the passenger side of the vehicle

**CFR §571.111; §571.111**: a section of the U.S. Code of Federal Regulations dealing with road vehicle mirrors

**co-experimenter, confederate**: a qualified individual who assists a lead experimenter in conducting an experiment

**confederate vehicle**: a vehicle driven by a co-experimenter or confederate during an experiment; such a vehicle provides necessary support for the desired scenario

**deg**: angular unit of measurement, degree

**DGPS**: differential GPS, differential global positioning system

**E.U.**: the European Union

**F**: a flat (planar) mirror (within manufacturing tolerances)

**F-D**: an F mirror used, or to be used, on the driver side of the vehicle

**F-E; F-Elongated**: a flat mirror that is longer than the F mirror vertically (and is flat within manufacturing tolerances)

**F-Elongated-D**: an F-E mirror used, or to be used, on the driver side of the vehicle

**FARS**: Fatality Accident Reporting System (a fatal accident database)

**F.O.V.; FOV**: angular field-of-view

**GM**: General Motors Corporation

**GES**: General Estimates System (an accident database)

**I**: the interior flat (center) mirror of a light vehicle

**LCG**; Last comfortable gap: the least distance that a driver would feel comfortable pulling into an adjacent lane in front of an oncoming vehicle, to pass. (Further defined in the text of this report.)

**magnification**: a term used in straightforward optical analyses to indicate size effects created by lenses and mirrors; a standard definition in optics

**minification**: the ratio of apparent image size seen in a nonplanar mirror as compared with the image size seen in a planar mirror in the same position; always less than unity for a convex or aspheric mirror

**NHTSA**: National Highway Traffic Safety Administration

**OEM**: original equipment manufacturer

**post hoc test**: a statistical test performed after the main tests, used to further specify significant differences

**reflectance; surface material reflectance**: a property of mirrors indicating the proportion of light that is returned; the "silvering" quality of the mirror; reflectance does not change with the curvature of the mirror

**reflectivity**: a property of mirrors indicating the proportion of light returned, including the effects of mirror curvature; reflectivity is determined by two factors: surface material reflectance and curvature

**UMTRI**: University of Michigan Transportation Research Institute

**USPTO**: U.S. Patent and Trademark Office

**VTTI**: Virginia Tech Transportation Institute

**SAE**: Society of Automotive Engineers (SAE, Inc.)

**Smart Road**: The Virginia Smart Road, located at VTTI in Blacksburg, VA. The Smart Road is used for roadway, vehicle, and driver research. It is closed to the public.

**SNK**: the Student-Newman-Keuls post hoc statistical test

**Tukey HSD**: the Tukey honestly significant differences post hoc statistical test

**ABSTRACT**

Aspheric outside rear-view mirrors (as defined here) are mirrors that contain a spherical inner portion and an (aspheric) outer portion with a decreasing radius of curvature. A vertical delineator separates the two portions. This type of mirror is intended to provide a wider field-of-view so that blind spots are minimized or eliminated. The mirrors are in common use in the European Union, but not in the United States, which specifically requires a flat mirror on the driver side for light vehicles.

This report is intended to provide an overview of available information on aspheric outside rear-view mirrors along with comparisons to spherically convex and flat mirrors. The objective is to provide a reference that presents the potential advantages and disadvantages of aspherics when applied to light vehicles. The report is composed of five parts: information retrieval, optical and mathematical analyses, static experiments, dynamic on-road experiments, and project findings. The information retrieval part reviews information appearing in the research and patent literature, as well as information online and from various manufacturers. Outside rear-view mirrors have been the subject of investigation for decades, so there is much to cover. The analyses lay the foundation for the optical aspects of the various mirrors. Specific emphasis is placed on mirror field-of-view, image minification, reflectivity, surface material reflectance, parameter measurements, mirror profile equations, and looming effects. The analyses are intended to improve understanding of the physical phenomena associated with the various mirror types. The static experiment part documents six experiments that were carried out. These involved measurement of the physical parameters of exemplars, objective measurement of reflected illuminance as a function of angle (which provides experimentally derived information on angular coverage of mirrors), evaluation of blind areas on each side of the light vehicle, distance estimation of mirror images by drivers, and finally, rated discomfort glare by both younger and older drivers. The dynamic (on-road) testing part describes an experiment performed on the Virginia Smart Road in which 12 different mirrors (7 on the driver side and 5 on the passenger side) were studied in realistic passing, merging, and gap acceptance maneuvers. The results are presented graphically for all significant changes as a function of mirror type, age group, gender, and maneuver type. The results show that aspheric mirrors do not cause substantive detrimental performance effects, but drivers found the distortion, uneasiness, and discomfort to be somewhat worse than for competing mirrors. The final part (Part V) of this document summarizes the project findings and draws main conclusions regarding aspheric mirrors as well as other types. The reader is referred to Part V for an overview of the findings. Three recommendations are provided, which involve future directions. The final recommendation involves developing and testing alternative outside rear-view concepts. Six suggestions for these alternatives are provided and described. In general, this document is intended to summarize all available knowledge regarding aspheric outside rear-view mirrors and associated conventional alternatives.

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## EXECUTIVE SUMMARY

Aspheric outside rear-view mirrors (as defined here) are mirrors that contain a spherical inner portion and an (aspheric) outer portion with a decreasing radius of curvature. A vertical delineator separates the two portions. This type of mirror is intended to provide a wider field-of-view so that blind spots are minimized or eliminated. The mirrors are in common use in the European Union, but not in the United States, which specifically requires a flat mirror on the driver side for light vehicles.

This report provides an overview of available information on aspheric outside rear-view mirrors along with comparisons to spherically convex and flat mirrors. The objective is to provide a reference that presents the potential advantages and disadvantages of aspherics when applied to light vehicles. The report is composed of five parts: information retrieval, optical and mathematical analyses, static experiments, dynamic on-road experiments, and project findings. The information retrieval part reviews information appearing in the research and patent literature, as well as information on-line and from various manufacturers. The analyses lay the foundation for the optical aspects of the various mirrors. Specific emphasis is placed on mirror field-of-view, image minification, reflectivity, surface material reflectance, parameter measurements, mirror profile equations, and looming effects. The analyses are intended to improve understanding of the physical phenomena associated with the various mirror types. The static experiment part documents six experiments that were carried out. These involved measurement of the physical parameters of exemplars, objective measurement of reflected illuminance as a function of angle (which provides experimentally derived information on angular coverage of mirrors), evaluation of blind areas on each side of the light vehicle, distance estimation of mirror images by drivers, and finally, rated discomfort glare by both younger and older drivers. The dynamic (on-road) testing part describes an experiment performed on the Virginia Smart Road in which 12 different mirrors (seven on the driver side and five on the passenger side) were studied in realistic passing, merging, and gap acceptance maneuvers. The results are presented graphically for all significant changes as a function of mirror type, age group, gender, and maneuver type. The results show that aspheric mirrors do not cause substantive detrimental performance effects, but drivers found the distortion, uneasiness, and discomfort to be somewhat worse than for competing mirrors. The final part (Part V) of this document summarizes the project findings and draws main conclusions regarding aspheric mirrors as well as other types. Three recommendations are also provided. In general, this document is intended to summarize all available knowledge regarding aspheric outside rear-view mirrors and associated conventional alternatives. The results of the five parts of the report are summarized in the following sections of this executive summary.

### Information Gathering

The information gathering task described in Part I of this report shows very clearly that outside rear-view mirrors have been a subject of study for decades. A huge variety of mirrors has been tested and developed, but few have survived to present vehicle applications. Even fewer have become standard on new vehicles.

Outside rear-view mirrors represent a compromise among many competing factors. Field-of-view, mirror size, reflected image size, glare, driver use, and driver acceptance are among the factors that must be considered. The United States has settled on a specific set of requirements for light vehicles and the European Union has settled on a somewhat different set. Initial indications from the information gathering task suggest that allowance for aspheric mirrors may be promising.

The general conclusions of the literature review are as follows:

- U. S. light vehicle regulations do not specifically prohibit the use of aspheric mirrors. However, mirrors must in any case meet the regulations requiring a flat mirror on the driver side and a flat or convex mirror on the passenger side (if a mirror is used). If a convex mirror is used on the passenger side, a precautionary legend must be included on the mirror reading, "objects in mirror are closer than they appear."
- Clearly, if an aspheric mirror is used on the driver side in the United States, it would have to have an infinite *vertical* radius of curvature, unless the regulations are modified to permit convex mirrors. On the passenger side, the outer aspheric portion must be in addition to a convex inner mirror that meets the U.S. regulations.
- E.U. regulations permit the use of aspheric mirrors on either side of a light vehicle. There are specific limits on curvature, but these do not impinge on currently accepted European mirror designs anyway (current E.U. aspheric mirrors are well within the specific limits on curvature). The regulations use a specific mathematical horizontal profile for aspherics, which is taken from Pilhall's (1981) formulation. This formulation is provided in the regulations without a clear explanation. For example, no coordinate system is defined. The current report has developed the details of the formulation.
- There is preliminary database information suggesting that vehicles equipped with aspherics are involved in fewer crashes than those equipped with flat mirrors. However, there is no reliable difference between vehicles equipped with convex mirrors and those equipped with aspherics. In other words, the difference in crashes is between vehicles with flat mirrors and vehicles with either convex or aspheric mirrors. (The databases examined were for European countries.)
- A flat mirror on the driver side of the vehicle appears to create a blind spot that is large enough to hide a vehicle. This blind spot is a result of lack of coverage occurring between head-turned direct view peripheral vision and the mirror view, which is relatively narrow.
- Aspheric and convex mirrors minify the image of an object when viewed in the mirror. In addition, *aspheric* mirrors create some image distortion which further narrows the horizontal dimensions of the corresponding image. Available information (in the literature) does not indicate whether this distortion creates a problem for drivers. However, aspheric mirrors appear to be accepted in the European Union, suggesting that the distortion is not a serious problem or is at least acceptable. In addition, a study done in the United States and limited to an auto manufacturer's employees indicated that they generally preferred aspherics to their regular mirrors. However, auto manufacturer's employees are not necessarily representative of the driving public. (The on-road experiments performed as part of current project suggest that aspherics would be less well accepted than current mirrors and that distortion *is* a problem.)
- The literature suggests that a careful look should be taken at aspheric mirror use by older drivers. Specifically, it is often found that older individuals are somewhat more susceptible to both discomfort glare and disability glare. (This matter was also investigated in the current project.)

- More generally, both aspheric mirrors and convex mirrors increase the field-of-view over that of flat mirrors. This advantage is offset by the loss of unit magnification of the image that is associated with flat mirrors. Therefore, assuming that unit magnification is a desirable feature, there is a tradeoff in going to aspheric or convex mirrors (loss of unit magnification vs. gain of a wider field-of-view).

**Derivations and Analyses**

The analyses performed in Part II of this report indicate that many of the questions regarding aspheric, convex, and flat mirrors can be answered by straightforward analyses. Specifically, questions regarding image size, reflectivity, surface material reflectance, and mirror surface equations can be answered precisely using straightforward geometrical, optical, and mathematical considerations. Particular attention must be paid to getting the image minification factor associated with convex mirrors correct. To do so, derivations must be based on the angle subtended at the observer's eye. Otherwise, incorrect conclusions may be drawn.

Another important element of the analyses is obtaining a direct relationship between mirror radius of curvature and reflectivity. This relationship makes it possible to measure the characteristics of a mirror and then to determine both the mirror reflectivity as well as the surface material reflectance. The analyses show very clearly that as mirror radius of curvature decreases (that is, as curvature itself increases), image minification increases and mirror reflectivity decreases. This analytical background places the understanding of flat, convex, and aspheric mirrors on a solid footing and sets the stage for experimentation.

Specific conclusions from the analyses that were performed are as follows:

- An accurate assessment of image minification using a convex mirror requires a two step analysis. The first step is to calculate the virtual image distance and corresponding magnification (which is far less than unity), and the second step is to calculate the angle of the image subtended at the eye. This angle is compared to that occurring for a flat mirror in the same location. Image minification is itself an important specification of a convex mirror and in addition it can be easily related to mirror reflectivity.
- It is possible to relate image minification directly to mirror radius of curvature. The other parameters needed are the eye-to-mirror distance and the mirror-to-object distance (Equation 12, Chapter 7).
- It is also possible to calculate apparent distance to an object based on minification. (However, later experiments show that drivers do *not* estimate distance using minification alone, as will be summarized in the Static Experimentation summary that follows.)
- Image minification will be greater for a given mirror mounted on the passenger side of the vehicle than for the same mirror mounted on the driver side of the vehicle (Figure 6, Chapter 7). This is a result of the greater eye to mirror distance on the passenger side.
- Mirror reflectivity can be calculated by deriving the ratio of reflected illuminances (Equation 18, Chapter 8), and can be shown to be directly related to the square of the minification factor (Equation 19, Chapter 8).
- Radius of curvature of a mirror can be measured using a precision instrument (Figure 7, Chapter 9) and an appropriate derivation (Figure 8 and Equation 21, Chapter 9).

- Surface material reflectance can be measured directly for a flat mirror (Figure 9, Chapter 9), but must be derived from measurements for a convex mirror. This, however, is a straightforward procedure (Equation 25, Chapter 9).
- For typical convex mirrors used on the driver side of the vehicle, "looming" is not a serious problem until objects are within 10 ft (3.05m) of the mirror (Figure 10, Chapter 10). Consequently, at typical pass and merge decision distances (which are much greater than 10 ft), looming is not a problem.
- Similarly, although slightly larger on the passenger side, looming is not a problem at typical pass and merge decision distances (Figure 11, Chapter 10).
- The equations for the horizontal profiles of aspheric mirrors that are used in the European Union involve a constant radius inner portion and an additional cubic in the outer (aspheric) portion (Equation 29 and Figure 12, Chapter 11). It is possible to take a few geometric measurements and then completely specify the equations.
- Reflectivity from the aspheric portion of an aspheric mirror can be calculated (Equation 34, Chapter 11), provided that the point of reflection is specified. This reflectivity is always smaller than for the convex portion.

**Static Experimentation**

The six experiments described in Part III provide several results that are in agreement with the analytical studies and serve to verify those studies. However, new information is also obtained that goes beyond the analyses and could not have been predicted. In most cases this information has to do with driver responses to the mirrors.

Specific conclusions are as follows:

- Typical sets of mirrors obtained for a vehicle marketed in both the United States and the European Union were found to be relatively precise in that the nominal radii of curvature were close to the actual radii of curvature (Table 2, Chapter 12). Similarly, the nominally flat mirrors were in fact nearly flat.
- The mirrors had consistent surface material reflectances (Table 3, Chapter 12). These reflectances were calculated from equations derived in Part II, based on measured parameters.
- Objective in situ tests indicate that there is a sharp cutoff of light reflected into the driver's eyes by flat mirrors, and that these mirrors also create the highest reflectivity values by a wide margin. Cutoffs are at approximately 12 deg on the driver side and 7.5 deg on the passenger side (Figure 17, Chapter 13).
- The tests also indicate that the reflectivity decreases as the mirror radius of curvature decreases. Furthermore, the cutoff angles increase. For example, a 2,000 mm convex mirror has cutoffs of approximately 21 deg on the driver side and 16.5 deg on the passenger side. Aspheric mirrors, on the other hand, have a gradual cutoff (actually a roll-off). Consequently, while they have the same initial reflectivities as their corresponding convex mirrors, the reflectivities taper sooner and go out to larger angles (Figure 17, Chapter 13). These results indicate that aspheric mirrors have larger fields-of-view and will also pick glare from larger angles but with much lower reflectivities.

- The reflectivity results (see for example, Figure 18, Chapter 14) are useful in determining the relative fields of view of the various mirrors, both on the driver side and on the passenger side.
- The distance estimation experiment showed, surprisingly, that drivers generally underestimate the distance to objects seen in the driver side rear-view mirror. Underestimation is "safe" estimation, because actual clearances are then greater than the drivers perceive them to be.
- Drivers do not appear to judge distance on the basis of image size. Image size for convex and aspheric mirrors is much smaller than for a flat mirror. A typical image size for a convex mirror would be half that of a flat mirror. This would correspond to an approximate doubling of the estimated distance and would result in a severe distance overestimation, that is, a potentially dangerous situation (Equations 14 and 15, Chapter 7). Clearly, drivers have learned to compensate for the image minification that occurs with convex mirrors.
- Flat mirrors produce the greatest and most consistent underestimation (Figure 32, Chapter 16). The greater the mirror curvature (that is, the smaller the radius of curvature), the smaller is the amount of *underestimation*. In fact, for a nominal distance near 100 ft (30.5 m) and a radius of curvature of 1,400 mm there was a slight over-estimation of distance. The results are generally consistent with earlier work, showing that the amount of underestimation of distance decreases as mirror radius of curvature increases. The net effect of replacing flat mirrors with convex mirrors is likely to be that some clearances associated with merging and passing would be smaller. There would also then be a greater likelihood of a collision owing to misjudgment of distance, but this must be traded against the likely increased probability of detection of nearby vehicles.
- The subjective experiment on headlight glare showed results consistent with previous analyses. Flat mirrors did indeed produce the highest ratings of reflected glare. At close distances, headlights move out of the field-of-view of the mirrors owing to their narrow field-of-view (Figure 38, Chapter 17).
- The outside mirrors generally produce glare ratings that are higher than those for an interior mirror that is adjusted to the manual nighttime setting. This indicates that typical outside mirrors are capable of producing substantially more discomfort glare, unless they are purposely darkened. However, darkening may affect daytime detection.
- Aspheric and convex mirrors having a 1,400 mm radius of curvature produce lower glare ratings than other outside mirrors tested, as compared with flat mirrors or mirrors with less curvature, as would be predicted by the reflectivity equations derived earlier. The glare ratings for 1,400 mm radius of curvature mirrors average about one rating value higher in glare than the inside rear-view mirror in the nighttime setting (Figure 38, Chapter 17).
- Older drivers gave *lower* glare ratings than younger drivers at distances beyond 30 ft (9.1 m) (Figure 35, Chapter 17). While this result may appear not to agree with the literature, there was one previous study on headlight glare that did show this same type of reverse effect. In both cases, subjects looked directly into the glare source in making their ratings. It is believed that under these conditions, older subjects give lower ratings of glare. Examination of the data by subject shows no outlier effects (Figures 42 and 43, Chapter 17), suggesting that the current results are very likely to be repeatable and are therefore considered to be reliable.

## On-Road (Dynamic) Experimentation

It should be noted that all on-road experimental results were obtained with the interior rear-view mirror in place (that is, available to the driver).

- On the basis of the results it appears that outside rear-view mirrors do not play a major role in passing, merging, and determining last comfortable gap. Drivers rely on their interior rear-view mirror as the primary source of reliable information, when rear-views are needed. However, when the outside mirror is flat (on the driver side), they may supplement the interior mirror with the outside flat mirror for reliable information.
- Outside rear-view mirrors at most have only a small influence on cut-in distance and gap acceptance. Flat mirrors produce slightly more clearance than do other mirrors.
- Glance patterns support the above conclusions, but younger drivers do use their outside mirrors a bit more than older drivers. Older drivers on the other hand look toward the forward view a bit more.
- Opinion data suggest that drivers are somewhat reticent to accept the newer mirrors. They find the distortion, uneasiness, and discomfort to be somewhat more troublesome. This result differs substantively from the earlier results of Flannagan and Flannagan (1998) who found good acceptance of aspherics among Ford employees, even initially. In addition, those employees also used the mirrors over a relatively long period of time. Flannagan and Flannagan found not only the high levels of initial acceptance, but also even better levels after extended use. The Ford employees could be considered to be much more knowledgeable than average drivers. Perhaps that is the reason for the difference in initial results. There are other age and gender effects, which suggest that older drivers in general and older female drivers in particular are less likely to accept (or "like") the newer mirrors.
- The elongated flat mirror on the driver side received relatively high ratings, but in general all performance differences as a function of mirror type were small.

## General Conclusions

This project reviewed the available information on outside rear-view aspheric mirrors and their relationships to convex and flat mirrors. In addition, optical and mathematical analyses have been carried out for the various types of mirrors. And finally, both objective and subjective static experimentation as well as dynamic experimentation has been performed to verify and add to the understanding of the various mirrors and how they are used.

The advantages of an aspheric mirror are as follows:

- It provides a substantially larger field-of-view than a corresponding flat mirror.
- The on-road experiments demonstrated no major performance *disadvantages* in ordinary passing, merging, and gap acceptance.
- It provides a larger field-of-view than a corresponding convex mirror (having the same radius of curvature as the spherical part of the aspheric mirror).
- It appears to induce fewer crashes than a corresponding flat mirror. (A convex mirror also appears to induce fewer crashes than a corresponding flat mirror.)

- Driver acceptance of an aspheric mirror appears to be satisfactory, based on the literature. However, the on-road dynamic experimentation performed during the current project indicates otherwise. Subjects indicated reticence by their ratings of distortion, uneasiness, and discomfort.
- Peak glare is substantially less for a typical aspheric mirror as compared with a flat mirror. The glare rolls off more rapidly than for a convex mirror (but does go out to larger angles).
- Older drivers generally rate the glare from outside mirrors lower than younger drivers for headlight distances at or beyond 30 ft (9.1m). Glare reflected from an aspheric does not create an additional burden of discomfort for older drivers (as compared with younger drivers) at least for the case where drivers are looking directly into the mirror.
- Drivers are generally able to compensate for the non-unit magnification of an aspheric (in its convex region) or convex mirror in terms of distance estimation. Generally (but not always), drivers underestimate distance to objects slightly.

These advantages are offset by disadvantages associated with an aspheric mirror:

- It produces image distortion in its outer (aspheric) portion. This distortion "squeezes" the horizontal dimension relative to the vertical dimension. The on-road tests indicated lower ratings for these mirrors as a result of the distortion.
- Since an aspheric provides a wider field-of-view, it then will pick up additional glare sources. However, these additional sources will be greatly attenuated.
- The amount of underestimation of distance that will occur with an aspheric (or with a convex mirror) will be less than for a flat mirror. Underestimation is a safety factor in that the true distance to an object is greater than the perceived distance. It is possible therefore that an aspheric (or convex) mirror may cause slightly smaller clearances during passing and merging, as well as an occasional collision. However, preliminary accident analysis performed by other researchers suggests that these types of collisions are more than offset by increased angular detection capability.
- All drivers, but particularly older drivers (and even more particularly female older drivers) appear reticent to accept and use aspheric mirrors, as evidenced by their ratings of distortion, uneasiness, and discomfort.
- Unit magnification, which is used by drivers to judge distance, is only available with flat mirrors. Convex and aspheric mirrors do not have unit magnification. Consequently, unit magnification will be lost if the current driver-side mirror is replaced with an aspheric (or convex) mirror.

**Recommendations**

There is no "correct" or unique answer regarding what recommendations should be made, since the results demonstrate tradeoffs that can be resolved in various ways. In making the recommendations, it should be recognized that the driver-side outside mirror problem is somewhat different from the passenger-side outside mirror problem. While both were studied in the current report, the two sides should be given separate consideration for reasons that have already been stated.

Recommendation 1. Based on all evidence, it is clear that aspheric mirrors are not a panacea. They have advantages and disadvantages. There is risk associated with permitting them to be used in place of current mirrors on light vehicles, particularly on the driver side. The main risk appears to be lack of acceptance or lack of adaptation. Another risk is loss of the unit magnification attribute on the driver side of the vehicle. The type of aspheric used in the European Union cannot be used on the driver side in the United States without modification of CFR §571.111. Therefore, prior to any change in the standard, it is believed that a fleet study should be performed over a substantial period of time, perhaps three to six months. The purpose of this study would be to examine the longitudinal (that is, the time-related) effects of using aspherics.

By performing a longitudinal study, it should be possible to determine if drivers adapt to the new mirrors. In addition, by examining incidents and any crashes, it might be possible to make an assessment of the potential reduction in sideswipe crashes resulting from the likely advantage of elimination of blind spots.

Recommendation 2. The current research report indicates that there has been no experimental attempt to study the supposedly increased detection capability of aspherics in a practical setting. Only optical fields of view were studied (see Chapters 14 and 15). This remaining element could be studied using an approach developed for heavy vehicles (Jenness, Llaneras, & Huey, 2005) in which electro-transmissive window coverings were used to assess how quickly and how accurately drivers of heavy vehicles could detect targets (other vehicles and objects) in their mirrors. All work was done statically, that is, with the vehicle under test standing still. While this approach has limitations, it might be helpful in determining if drivers can actually use the aspheric portion of aspheric mirrors. It would not be necessary to use electro-transmissive panels. Instead, the outside mirror under test could simply be blocked from view to limit the visual sample time, as called for in the report by Jenness et al. (2005). Such a test should shed light on the potential accuracy of detection, accuracy of identification, and response time. Of course, comparison tests are always preferred, so it would prudent to include competing mirrors in the test.

It should be understood that testing of this type might be indicative, but it would not be conclusive. Since tests would be performed statically, even positive results for aspherics would have to be checked by some type of on-road study.

Recommendation 3. It is believed that there are potential alternatives for outside mirror design, other than the aspheric. For example, all heavy vehicles have a flat mirror by regulation and a convex mirror by recommended practice on each side of the vehicle (Spaulding, Wierwille, Gupta, & Hanowski, 2005). The two mirrors are used in combination to obtain an adequate field-of-view and simultaneous indication of "true" distance where needed. It would seem that some derivative of this design could be used for light vehicles. Another alternative is to take advantage of video technology to enhance the field-of-view and eliminate blind spots. It should be possible to develop video displays at the A-pillars or another location close to the current actual mirrors for purposes of wide angle viewing and elimination of blind spots.

## PART I: INFORMATION RETRIEVAL

Research and development in regard to 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 United States and mirrors used in the European Union. While the United States has stayed with outside rear-view mirrors that are flat or convex, the European Union 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 United States or the European Union. 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 observer, and the specific definition is that the mirror surface is spherical (again, within manufacturing tolerances). 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 inner portion; and an outer portion that increases in curvature, horizontally. The two portions are separated by a vertical solid or dashed line that is etched into the mirror. The intent of increasing the curvature of the outer portion is to increase the field-of-view of the mirror even though some image distortion may occur. It should be noted that the outer portion of an aspheric mirror is called the aspheric portion or aspheric region. The inner portion, usually being convex, is accordingly referred to as the convex portion or region.

This specific definition is patterned after mirrors used in the European Union. It is possible to have other forms of aspheric mirrors. For example, it is possible to have a mirror with a gradual increase in curvature across the entire mirror from inside to outside. This type of mirror was not studied in the current research because it produces some horizontal image distortion regardless of the point of reflection. Instead, the research is focused on the above given specific definition. Consequently, unless stated otherwise, a convex mirror is considered to be spherical and an aspheric mirror is considered to be spherical in its inner portion and to have greater curvature in its outer portion, with a vertical line separating the two portions.

This research project had the objective of evaluating and comparing 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 in the United States. 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.

Part I of this report involves information retrieval, in which several sources are examined. The objective of Part I is to provide a concise overview of relevant documentation regarding aspheric mirrors along with any comparisons to other types of mirrors. Much of this process involves discussion of flat and convex mirrors, because these mirrors represent the main baseline for comparison, and because an aspheric mirror contains a convex portion.

# CHAPTER 1: COMPARISON OF U.S. AND EUROPEAN REGULATIONS

## Relevant Regulations

Regulations in Europe differ from those in the United States regarding rear-view mirrors. The Code of Federal Regulations (§571.111) in the United States requires mirrors on both the driver side and passenger side of a light vehicle (Office of the Federal Register, 2002). 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. Therefore, if an aspheric is used, it must be in addition to mirrors meeting the regulations. One manufacturer, Saab, is known to have used aspherics in the United States. The mirror is used on the passenger side, has a convex portion meeting U.S. regulations, and has a contiguous outer portion with increasing curvature. 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, 71/127/EEC (European Parliament and Council, 1988). Both spherical and aspheric mirrors provide a driver with an expanded field-of-view. European directive 2003/97/EC defines a spherical surface as having a constant radius of curvature in all directions. 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 spherical primary calotte with:
>
> $$y = R - \sqrt{(R^2 - x^2)} + k(x - a)^3$$
>
> R : nominal radius in the spherical part
> k : constant for the change of curvature
> a : constant for the spherical size and spherical primary calotte

Chapter 11 of the current report contains a more thorough explanation of this equation and corresponding ramifications, including reflectivity. The European directive does not provide this explanation and therefore cannot be easily interpreted without further explanation.

The intended purpose of the aspheric mirror is to increase the field-of-view while still maintaining a portion of the mirror that has a convexity less than that of a conventional convex mirror. One purpose of this would be to reduce image minification produced by the convex mirror. The 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.

Aspheric mirrors, although wide-angle, are classified as Class III mirrors; that is, mirrors on the driver and passenger side of light vehicles. As stated by the European directive, an exterior mirror in this class must be spherically convex or planar. However, the mirror may contain an aspheric part if the main portion of the mirror fulfills the field-of-view requirement. The current European directive indicates the requirement for the aspheric portion of a Class III mirror as follows (European Directive 2003/97/EC, section 3.3):

> 3.3.1. Aspherical mirrors shall be of sufficient size and shape to provide useful information to the driver. This normally means a minimum width of 30 mm at some point.
> 3.3.2. The radius of curvature $r_i$ of the aspherical part shall not be less than 150 mm.

*Field-of-View*

The current U.S regulation (§571.111, exterior rear-view mirrors on light vehicles) calls for a unit magnification (planar) mirror on the driver side. If a mirror is used on the passenger side, it must be planar or convex. The planar mirror on the driver side must provide a reflected field-of-view that is 2.4 m (7.9 ft) wide, 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 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, 20 m (65.6 ft) behind the eyes of the driver. Furthermore, the directive calls for the road to be viewable 4 m (13.1 ft) behind the driver's eyes and 1 m (3.28 ft) in width. Figure 1, from European Parliament and Council Directive 2003/97/EC (section 5.3.2.), shows the required field-of-view for Class III mirrors for light vehicles.

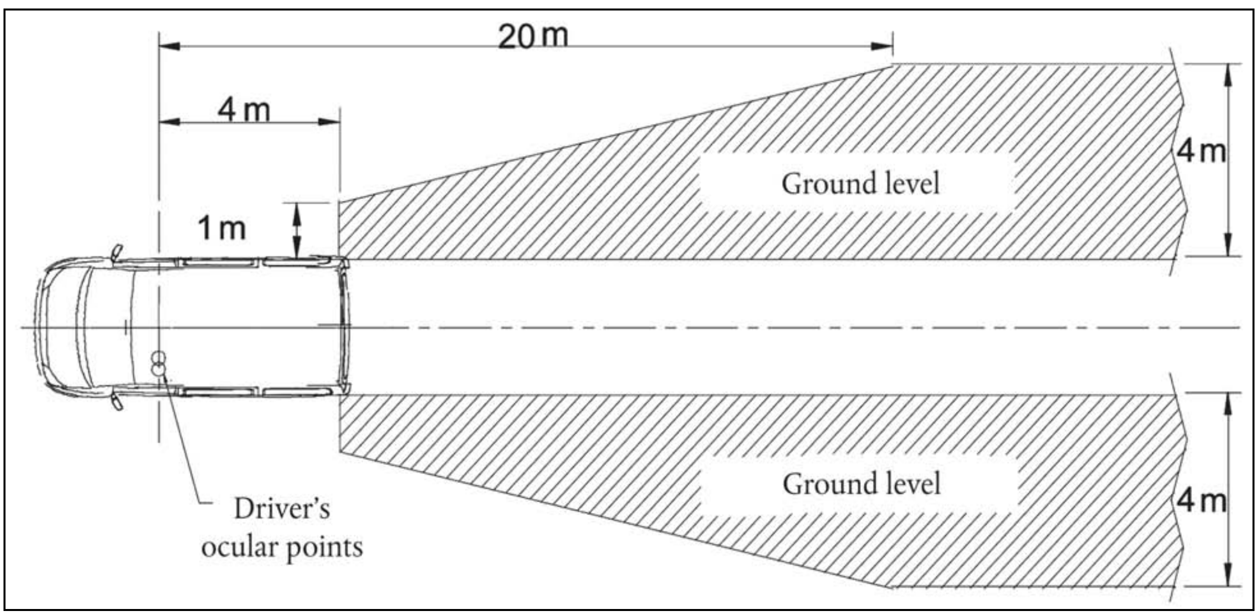


**Figure 1. Required fields-of-view for Class III mirrors for light vehicles. (From European Parliament and Council Directive 2003/97/EC (section 5.3.2.), 2003, Official Journal of the European Union.)**

*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 1,200 mm (47.2 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, as depicted in Figure 1 for Class III mirrors. Chapter 9 of the current report provides a detailed description of a methodology and apparatus that can be used to measure the radius of curvature and other mirror parameters.

# CHAPTER 2: HUMAN FACTORS ISSUES AND RESEARCH LITERATURE ASSOCIATED WITH ASPHERIC MIRRORS

## Image Changes

As previously noted, there are three main types of exterior rear-view mirrors in use on light vehicles in the United States and the European Union. These consist of planar (flat), convex, and aspheric mirrors. In the United States, only planar mirrors are permitted for use on the driver side of the vehicle because, at least theoretically, they do not distort the relative distance and closing speed of vehicles seen in the mirror. Also, as mentioned, convex mirrors can be used on the passenger side, but require an imprinted caution legend.

A planar mirror provides an image that is "unit magnification" (i.e., a reflected image that is the same size and distance as an identical object being viewed from the same distance without the mirror, CFR §571.111). An image produced in a convex mirror appears smaller than unit magnification (the angle subtended at the eye is smaller). The geometrical fields-of-view differences between images reflected from planar mirrors and images reflected from convex mirrors are described in greater detail in the Track 2 work plan document of the contract DTNH22-00-C-07007 (Wierwille, Spaulding, Hanowski, Koepfle, & Olson, 2003), pp. 74 to 81. These differences are also described in Chapters 7 through 10 of the current report.

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. This phenomenon is known as "looming" and is analyzed in Chapter 10 of this final report.

An aspheric mirror currently used in the European Union contains a spherically convex portion that is roughly two-thirds of the mirror and may also have a larger horizontal radius of curvature than that of a typical spherically convex mirror. The outer one-third of the mirror is the aspheric portion that is intended to increase the overall field-of-view. This configuration increases the area of coverage while still providing a portion of the image that has less optical minification than a typical U.S. convex mirror. Figure 2 depicts the images of a heavy vehicle as viewed in typical aspheric mirrors.

**Figure 2. Typical aspheric mirror images (driver side).**
**Note that the image produced in the spherical section (right side of dividing line) is minimally changed while the image in the aspheric portion (left of the dividing line) is distorted.**

Aspheric mirrors have become increasingly common on light vehicles in Europe. Recently, European Directive 2003/97/EC has been adopted to regulate the use of aspheric mirrors in the European Union. Typically, the spherical portion of the mirror will have a radius of curvature of

2,000 mm (6.56 ft). Although legislation in the European Union has recently been adopted regarding aspheric mirrors, they have been used on some vehicles for approximately 15 years.

### Blind Spot Reduction

Although the use of exterior rear-view mirrors increases the driver's field-of-view, there still exists a large blind zone for mirrors in the United States. 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 United States on the passenger side, the blind zone on the passenger side is smaller than the one produced on the driver side. The blind zone produced on the driver 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-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. This situation is shown in Figure 3.

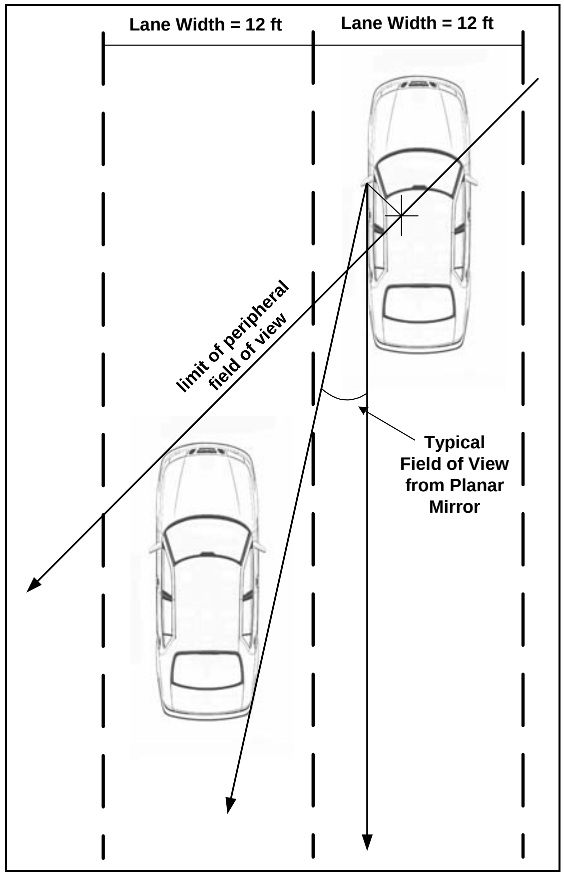


**Figure 3. Blind spot is large enough to conceal a vehicle.**

Flannagan et al. (1999) also indicated that the limit of peripheral field-of-view was probably less than 180 deg for older drivers, thereby resulting in an even larger blind zone. If the field-of-view of the driver-side 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 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. This concept is covered in greater detail in Parts II and III of the current report.

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, 1998; 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 convex mirrors are different from those made with planar 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, some of the samples may 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 et al. (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 percent. Again, this is an overestimation as compared with the underestimation that occurs with flat mirrors.

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

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. Also, the level of image disparity that causes the driver to see double images needs to be determined" (p. 11).

It should be recognized that the outer (aspheric) portion of the mirror would be used almost exclusively for presence/absence determination, that is, object 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 overestimated in convex mirrors (relative to flat mirrors, for which underestimation is the rule). This includes both spherically convex and aspheric mirrors. Flannagan, Sivak, and 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 side of the vehicle? One argument in favor of convex mirrors, particularly 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, 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 used 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 nor 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.

Before leaving the subject of gap acceptance, it is probably worthwhile to mention that automobiles of the early 1970s had large rear windows without raised trunks. Today's automobiles have slightly narrower rear windows with raised trunks, which may make use of the interior rear-view mirror for distance judgments more difficult. Part IV of the current report describes an on-road experiment involving gap acceptance, passing, and merging in a modern automobile using flat, convex, and aspheric outside rear-view 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 side of the vehicle. This preference for non-planar mirrors also increased after four weeks of use. The study was performed using 114 employees of 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-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 percent 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 that preference would likely increase in acceptance over time. There is a second indication of acceptance; since these mirrors are currently used on the driver side of many European light vehicles, the acceptability and preference for them is probably satisfactory. Acceptability of various mirrors is also examined in the road tests described in Part IV of the current report.

# CHAPTER 3: CHARACTERISTICS OF EUROPEAN ASPHERIC MIRRORS

## Overview

As indicated, European Directive 2003/97/EC is the current standard for the use of aspheric mirrors on light vehicles in the European Union. These mirrors use Pilhall's (1981) formulation. Included in Pilhall's study is a field test of a spherically convex mirror with an aspheric portion toward the mirror's outer edge. The radius of curvature of the spherical region was 2,000 mm (6.56 ft). It was stated that the majority of participants responded positively to the increased area of coverage provided by the mirror even though distance and speed information was distorted.

Aspheric mirrors currently in use are not very different from the ones used in the Pilhall (1981) study. According to de Vos (2000), aspheric driver-side mirrors in use on the road (previous to 1999) typically had radii of curvature averaging approximately 2,000 mm (6.56 ft) within the observed range of mirrors. Passenger-side mirror radii of curvature averaged around 2,000 mm (6.56 ft) as well, although there were fewer passenger-side aspheric mirrors in use in 1999. Field-of-view measurements for surveyed aspheric mirrors were not much different from spherically convex mirrors. Aspheric mirrors averaged an area of coverage approximately 29 deg while spherically convex mirrors averaged an area of coverage approximately 26 deg. This finding does *not* agree with experimental results reported later in the current report, Chapter 13. The latter results indicate that the field-of-view is markedly increased with the use of aspheric mirrors.

## European Driver Information

For a number of years, European drivers have been able to use aspheric exterior rear-view mirrors on both sides of the vehicle. Originally these mirrors were only available on higher-end vehicles but, more recently, these mirrors are becoming increasingly available on lower priced models as well. Research by de Vos (2000) and de Vos, Theeuwes, and Perel (2001) examines 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 side of the vehicle. One result of the survey was that 46 percent of the participants did not know that the image produced in a non-planar mirror is modified. Of these respondents, 15 percent 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 non-planar mirror on the driver side of the vehicle. Drivers stated that they would choose an aspheric mirror if given the option. Of course, these remarks must be tempered by the fact that drivers appear to know so little about the outside rear-view mirrors on their cars. Clearly, they provided erroneous answers to several basic questions. This early finding was considered in Part IV of the current report. Driver/subjects participating in the Part IV experiments were given descriptions of the mirrors used in the road tests, and they were requested to examine the mirrors ahead of the tests.

As previously discussed, gaps deemed acceptable for lane changing were only slightly smaller for convex mirrors than for planar mirrors (Mortimer, 1971; Mortimer & Jorgeson, 1974; Walraven & Michon, 1969). This result is attributed to the presence of the interior rear rear-view mirror. Following the survey experiment (de Vos, Van der Horst, & Perel, 2001; de Vos, 2000), these authors devised another experiment intended to examine gap acceptance with planar, spherically convex mirrors, and aspheric mirrors. Using a “last safe gap” method where a car approached from behind 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 side. 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 of 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 view would be blocked. Future research should examine gap acceptance and detection using planar, 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 only. As mentioned earlier, Mortimer (1971) examined gap acceptance from planar and convex exterior mirrors viewed in combination with planar interior mirrors. Direct comparisons between convex and aspheric conditions cannot be made because aspheric mirrors were not available at the time of the Mortimer study. Nevertheless, results from the study indicated that the difference in gaps for convex and planar exterior mirrors was not significant when the mirrors were used in combination with the planar interior rear-view mirror.

### 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 (see Chapter 7 of the current report). 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.

# CHAPTER 4: RELEVANT AGING DRIVER RESEARCH

## Older Driver Epidemiology

The population of older drivers (65 and older) is increasing. According to NHTSA (2000), in 1999 older drivers made up approximately 10 percent of all U.S. licensed drivers. The reported number of licensed older drivers increased 39 percent from 1989. Furthermore, according to the American Medical Association (AMA, 2003), driving related fatalities represent the second leading cause of injury-related deaths for older Americans. The older driving population is second only to the driver population under the age of 25 for the number of accidents per mile driven (AMA, 2003).

Based upon the information provided by NHTSA and the AMA, accident related vehicular injuries and fatalities are an increasing problem for older drivers. Some of these accidents may be preventable. A certain amount of physiological and mental functionality decline accompanies the aging process. However, such declines vary greatly among individuals. Waller (1991) states that older driver performance information is derived from group differences. When considering individual performance measures there is a major difference between chronological age and functional age. For example, one person may exhibit severe deterioration in performance by age 60, whereas another individual may experience very minimal, or no performance deterioration, even at a much later age. According to Waller (1991), there is an overall increased probability of performance-related deterioration (visual, cognitive, reaction time, etc.) accompanying the aging process. However, because of great individual variability, testing is necessary to determine what, if any, deficits an older driver may have.

## Visual Performance

As people age, their field-of-view, visual acuity, and contrast sensitivity tends to deteriorate (Ball & Owsley, 1991; Johnson & Keltner, 1983; Retchin, Cox, Fox, & Irwin 1988; Shaheen & Niemeier, 2001; Shinar & Schieber, 1991). Shinar and Schieber and Shaheen and Niemeier reviewed driving constraints of older people. According to these reviews, as older drivers' visual system deteriorations increase, their susceptibility to accidents resulting from poorer quality visual information increases.

According to Ball and Owsley (1991), there typically exists a decline in the useful field-of-view. The useful field-of-view is the visual area in which a person can obtain necessary information from a quick glance. This area is smaller than the peripheral field-of-view in that an object may be detectable far into the periphery, however, no useful visual information may be obtained from the object for purposes of decision making.

Information obtained from peripheral vision, even if it is simply object detection, could be very important when deciding whether or not to change lanes. Even if no other information may be obtained about the object, simply knowing it is there may help to reduce the possibility of a lane change-related collision. Retchin et al. (1988) reported that there is a field-of-vision loss due to aging. The useful field-of-vision of younger individuals is approximately 170 deg (maximum 180 deg). The useful field-of-vision of an individual approximately 50 years old can be reduced to 140 deg. By the time a person reaches 65, useful field-of-vision could average approximately

120 deg (Retchin et al., 1988). The blind spot produced by the planar mirror on the driver side was estimated to be large enough to conceal a vehicle (Figure 3). This is assuming the driver has a field-of-view of 180 deg. In some cases, this blind area may be even larger if the driver suffers from a loss of field-of-vision. Johnson and Keltner (1983) conducted a study with 10,000 participants on field-of-vision loss. Results from this study suggested that occurrences of field-of-vision loss were approximately 3 percent for all age groups under 60. For participants over age 65, visual field loss increased to approximately 13 percent.

*Detection/Search Performance*

Often, driving is a visually demanding task that requires a great deal of visual information gathering, interpretation, and decision-making. In addition to paying close attention to the highly dynamic area in front of the vehicle, drivers need to interpret areas to the sides of and behind the vehicle, typically using the rear-view mirrors. McGwin, Chapman, and Owsley (2000) interviewed and administered self-report questionnaires to older drivers. They found correlations that suggested older drivers with visual impairments tended to have greater difficulty in driving at night, driving in fast-moving, heavy traffic, and driving in the rain. Moreover, participants with a decreased useful field-of-view reported increased difficulty driving in inclement weather.

Ho, Scialfa, Caird, and Graw (2001) studied effects of clutter and ambient light conditions on older drivers. This study focused on the forward area-of-view of the vehicle. In general, younger and older participant groups were equally affected by increased clutter. However, older participants typically required more time to fixate and achieve similar results when compared to those achieved by younger drivers. The study was static, and participants were not limited in terms of field-of-view blockage or time for detection tasks. It was suggested that driving in highly complex, dynamic environments involving the need for quick decision making could be more difficult, on average, for older drivers. Although the study by Ho et al. (2001) took into account only the forward area-of-view, the reflected area located within the forward area-of-view may further slow decision-making efforts by adding another task component. A driver must attend to the forward environment while, at the same time, locating objects to the sides and rear using the external rear-view mirrors or direct quick glances.

## Glare

Drivers typically experience some form of visual performance deterioration at night as a result of glare. This visual performance degradation seems to become more of a problem with older drivers. Many studies have been done to examine glare in both younger and older drivers (Anderson & Holliday, 1995; Lockhart & Atsumi, 2004; Pulling, Wolf, Sturgis, Vaillancourt, & Dolliver, 1980; Shinar & Schieber, 1991, Theeuwes, Alferdinck, & Perel, 2002). Theeuwes et al. (2002) defines glare as a “blinding experience that results from a bright light source in the visual field-of-view.” Glare can result from many different sources including bright lights from the surrounding environment (such an urban environment), headlights from oncoming vehicles, and bright lights being reflected into the eyes of the driver via the rear-view mirrors.

There are two commonly accepted forms of glare: discomfort glare and disability glare (Sanders & McCormick, 1993). Disability glare is defined as a type of glare that causes poorer performance on tasks. Although the effects of disability glare can differ greatly among individuals, older drivers tend to be affected more than younger drivers. The second type of glare is discomfort glare. This type of glare is much more common and causes annoyance or discomfort without necessarily impairing performance. Anderson and Holliday (1995) found that glare resulting from oncoming headlights could reduce the ability to judge motion. In a simulated environment where opacity was increased (simulating such visual degradations as cataracts), visual performance was worse. This may suggest that older individuals with visual impairments are more likely to experience performance degradation due to glare.

A study by Lockhart and Atsumi (2004) examined effects of glare reflected from planar and non-planar rear-view mirrors. In a static setting, the glare source was mounted to a fixed point and then rotated toward the mirror for each trial. This study utilized a de Boer rating scale to examine discomfort glare in younger and older drivers (de Boer & Schreuder, 1967). It was found that older drivers tended to notice glare sources later than younger drivers. Moreover, the glare ratings from older drivers indicated greater discomfort than younger drivers. In general, rated discomfort resulting from the non-planar mirror was less than that reported from the planar mirror. One limitation of the study however, was that the surface reflectance of the planar mirror differed from that of the non-planar mirrors. The authors concluded that both younger and older participants experienced less discomfort when using a non-planar mirror. These results are in agreement with the analyses of Chapters 7 through 9, and 11, which show that reflectivity decreases as curvature increases.

### Perception

Although there are physical changes accompanying the aging process, perceptual changes occur as well. These changes do not necessarily result in performance deterioration, but rather result in attitudinal and habitual changes. Simply put, older drivers tend to change the way they drive. Studies have been done to examine these differences (Nishida, 1999; Stelmach & Nahom, 1992; & Wolffelaar, Rothengatter, & Brouwer, 1991).

Research results by Stelmach and Nahom (1992) state that older drivers take more time to reach a decision and that reaction time tends to be slower. This can be compounded by task complexity as well. However, if given enough time, older drivers tend to be more accurate than younger drivers. As stated by Stelmach and Nahom, "older adults are more worried about making errors and, consequently, slow their rate of response."

Wolffelaar et al. (1991) conducted research on traffic merging and found that older drivers' response times were much slower than younger drivers. Older participants also viewed risky situations much more conservatively than younger participants. Participants were required to view traffic merging situations and report whether or not it would be safe to merge. It was stated that if given enough time to make a decision, taking into account more conservative safety behavior, results from older participants did not indicate problems arising from functional impairments. Older participants simply waited longer for safer merging conditions.

Nishida (1999) examined older drivers' reaction time and behavior. Again, it was found that older participants' reaction times were significantly longer than those of younger participants. However, behavior was modified to overcome this. Older participants drove slower with more distance between their car and the car in front of them. It was concluded that this behavior helped compensate for slowed reaction time. Even though age-related physical and mental deterioration can occur in older drivers, compensatory changes to behavior and risk assessment are likely to help overcome performance degradations.

### Summary

Performance deterioration tends to accompany the aging process. Older drivers however, typically alter driving behavior to compensate for this deterioration such that the effect on driving performance is minimized. Previous research shows that older drivers may benefit from non-planar, or even aspheric, mirrors by providing an expanded area-of-view (Ball & Owsley, 1991; Johnson & Keltner, 1983; Retchin et al., 1988; Shaheen & Niemeier, 2001; Shinar & Schieber, 1991), by reduction of glare (Anderson & Holliday, 1995; Lockhart & Atsumi, 2004; Pulling, Wolf, Sturgis, Vaillancourt, & Dolliver, 1980; Shinar & Schieber, 1991, Theeuwes, Alferdinck, & Perel, 2002) and by potentially aiding perceptual detection of vehicles (Nishida, 1999; Stelmach & Nahom, 1992; and Wolffelaar, Rothengatter, & Brouwer, 1991).

## CHAPTER 5: MIRROR-RELATED CRASHES

### Overview

In 2002, approximately 9.9 million vehicles were involved in crashes. Of these crashes, it is estimated that 7 million resulted in property damage only, 2.9 million resulted in injury, and 49,464 fatalities occurred (NHTSA, 2002). Of the crashes involving only property damage, 4.4 percent (306,000) were from merging/lane changing maneuvers and 1.6 percent (109,000) resulted from passing another vehicle. Of the crashes involving injury, 2 percent (59,000) were from merging/lane changing maneuvers and 1.1 percent (31,000) resulted from passing another vehicle. Of the fatal crashes, 1.7 percent (854) resulted from merging/lane changing maneuvers and 2.1 percent (1,052) resulted from passing another vehicle. These statistics, taken from Traffic Safety Facts, 2002, were obtained from the Fatality Analysis Reporting System and General Estimates System 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.

### European Rear-View Mirror Related Lane Change Accidents (Finnish/UMTRI Findings)

There is evidence that convex mirrors on the driver side of European vehicles help to reduce crashes. Luoma, Sivak, and Flannagan (1995) examined light-vehicle lane change crashes related to exterior mirror type 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 side reduced crashes during driver-side lane changes by 22 percent. These results suggest there is some benefit to having non-planar driver-side mirrors.

Schumann, Sivak, and Flannagan (1996) examined whether or not convex mirrors installed on the driver 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 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 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 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 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 percent. 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 side of the vehicle. However, there is no evidence suggesting that one type is better than the other.

# CHAPTER 6: CURRENT PRACTICES AND AVAILABLE PRODUCTS

## Patent Search

A search of U.S. Patent and Trademark Office documents was conducted to find potential exterior aspheric mirror related concepts. Terms searched included various combinations of: vehicle, mirror, rear-view, aspheric, wide-angle, non-planar, and multi-radius. The methodology behind the terms used was to consider all possible patented concepts relevant to aspheric mirrors and blind spot reduction. As previously indicated, an aspheric mirror contains a spherically convex region, with a large radius of curvature on approximately the inner two-thirds of the mirror. The outer portion of the mirror contains a region of decreasing radius. Patents similar to this description were found. In addition to aspheric mirrors, the results included patented concepts that address blind spot visibility in different ways.

Pilhall (1981) introduced the concept of using a mirror with a decreasing radius on the outer edge as a way to reduce the blind zone in the direct proximity of the vehicle. Many of the patents found date back to the early 1980s and before. U.S. patents pertaining to aspheric mirrors are listed in Table 1.

U.S. Patent 5,793,542 (1998) was the most recent aspheric-related concept found. This exterior rear-view mirror concept employs a gradually changing radius of curvature for the top and bottom portions of the mirror as well. The outer portions of the mirror contain the smallest radii of curvature while the inside portions of the mirror contain the largest radii of curvature. In relation to this concept, earlier Patents 3,764,201 (1973) and 2,778,273 (1957) both describe exterior mirrors with areas of gradually increasing curvature. Patent 3,764, 201 (1973) employs a planar, west coast style, mirror with an area of increasing curvature on the outer edge of the side, top, and bottom portions of the mirror. This concept is intended for heavy trucks and buses. Patent 2,778,273 (1957) describes an exterior mirror for use on light vehicles. The mirror consists of a central planar portion surrounded by an annulus of increasing curvature.

**Table 1. U.S. patent search results pertaining to aspheric mirrors.**

| | Patent Number | Inventor(s) | Patent Date | Title |
|---|---|---|---|---|
| Exterior multi-radius mirror concepts | 5,793,542 | Kondo, H, Oota, S., Yamada, T., Oota, H., & Kondo, H. | August 11, 1998 | Automobile mirror assembly |
| | 5,005,962 | Edelman, K. | April 9, 1991 | Rear-view mirror |
| | 4,331,382 | Graff, H. | May 25, 1982 | Wide-angle mirror for automobiles and the like |
| | 4,264,144 | McCord, R. | April 28, 1981 | Rear-view mirror |
| | 4,258,979 | Mahin, W. | March 31, 1981 | Rear-view mirror assembly |
| | 3,764,201 | Haile, E. | October 9, 1973 | Rear vision mirror |
| | 3,628,851 | Robertson, H. | December 21, 1971 | Wide angle rear-view mirror |
| | 3,389,952 | Tobin, J. | June 25, 1968 | Exterior mirror assembly for vehicles |
| | 2,778,273 | Fellmeth, R. | January 22, 1957 | Rear-view mirror |
| | 2,279,751 | Hensley, E. | September, 14, 1940 | Rear-view mirror |
| Other related concepts | 6,547,405 | Jacobs, R. | April 15, 2003 | Vehicle side-view mirror blind spot adjustment method |
| | 4,223,983 | Bloom, S. | September 23, 1980 | Wide angle mirror attachment for vehicle side-view mirrors |
| | 2,857,810 | Troendle, J. | October 28, 1958 | Mirror for vehicles |

Patents 4,331,382 (1982), 4,264,144 (1981), and 4,258,979 (1981) are examples of concepts very similar to aspheric mirrors currently in use. Patent 4,331,382 (1982) consists of a planar, or large-radius, spherically convex mirror with an area of increasing horizontal curvature on the outer edge of the mirror. Approximately three-fifths of the mirror surface has a constant radius of curvature or is flat, whereas approximately two-fifths of the surface is an area of increasing curvature. Patent 4,264,144 (1981) consists of a spherically convex or planar inner mirror surface with a very gradual increase in curvature across the entire surface of the mirror. The methodology described by the patent was to reduce any negative effect of distortion as an object passed from the area of mirror with the least curvature to the area of the mirror with the most curvature. Patent 4,258,979 (1981) is a mirror concept consisting of a planar segment and a portion containing a gradually decreasing horizontal radius of curvature toward the outer edge. Also included in the concept is an area of decreasing radius along the bottom edge of the mirror.

Earlier patents 3,628,851 (1971) and 2,279,751 (1940) provided an expanded field-of-view by using multiple planar portions fixed at different angles within the same mirror. Patent 3,628,851 (1971) consists of a planar mirror area and, toward the outer edge of the mirror, an additional planar segment angled outward to provide a greater field-of-view. Patent 2,279,751 (1940) utilizes a west coast style planar mirror for buses and incorporates angled planar sections on the outer and bottom edges of the mirror to expand the field-of-view.

Also related to current aspheric mirrors are patents 5,005,962 (1991) and 3,389,952 (1968). Both concepts consist of a planar driver-side mirror with a spherically convex mirror segment on the outer edge. In Patent 5,005,962 (1991) the planar mirror and the convex mirror are each parts of the same surface material, whereas, patent 3,389,952 (1968) consists of separate planar and convex mirrors within the same housing.

*Other Concepts*

In addition to multiple aspheric-type concepts, other mirror-based concepts designed to enhance field-of-view were also researched. Included in Table 1 are three examples of patents found that increase the field-of-view over that of a conventional mirror. Patent 2,857,810 (1958) describes a concept for an aspheric interior rear-view mirror. The mirror consists of a planar central portion with areas of increasing horizontal curvature on both sides of the mirror. This concept illustrates an early attempt to increase visibility around a vehicle.

Patent 4,223,983 (1980) is an example of a supplementary mirror that adheres to a standard exterior mirror. It uses a small rectangular-shaped mirror of gradually increasing curvature housed in a box or frame. The small mirror assembly attaches to the larger exterior rear-view mirror using an adhesive.

Finally, another type of enhancement designed to increase the field-of-view is a fairly recent concept. Patent 6,547,405 (2003) is an example of a motorized pivoting mirror. With this device the driver is able to use a control to increase or decrease the angle of the mirror, thereby overcoming the blind spot. The mirror concept also contains markings on both sides of the mirror to aid the driver in adjustment.

## Available Aftermarket Product Search

A search of available products was conducted via the internet to determine what is currently available. Included in the search were OEM mirrors, aftermarket products, and the availability of imported aspheric mirror surfaces. Results of this search suggest that both aftermarket mirror surfaces and imported mirrors are available, but with several exceptions.

Although OEM aspheric mirrors are becoming increasingly available as standard equipment on light vehicles in the European Union, the same mirrors are not available on U.S. vehicles. Moreover, these mirrors are not available as optional equipment. As indicated earlier, only one known automotive manufacturer (Saab) equips vehicles with passenger-side aspheric mirrors as standard equipment. Because of the current standard, however, aspheric mirrors are not permitted on the driver side of a vehicle. The Saab passenger-side aspheric mirror meets the U.S. Federal standard because it contains a spherically convex portion which meets the standard.

Aftermarket aspheric-type mirrors are available for purchase in some cases. MultiVex Mirrors manufactures mirrors of increasing (horizontal) curvature for a wide array of light vehicles.

These mirrors simply attach over the existing OEM mirrors. They are available for both the passenger side and driver side of the vehicle. MultiVex mirrors have a different geometry than conventional European aspheric mirrors. Whereas European aspheric mirrors contain a region of spherical convexity and a region of increasing horizontal curvature, MultiVex mirrors consist of a surface of gradually increasing horizontal curvature. Thus, no spherically convex region exists and there is no delineation separating the spherical and aspheric portion of the mirror. It is important to point out that aftermarket parts suppliers are not subject to the Federal standards. Such standards only apply to newly manufactured vehicles.

There are numerous businesses that import and distribute parts for European vehicles. Included in many of the imported parts inventory lists for various European vehicles are European aspheric mirror surfaces available for purchase. Typically these mirrors are listed for both the driver side and passenger side of the vehicle provided that both mirrors are available on the vehicle in Europe. In addition to part suppliers, there are numerous Web sites providing instructions for the installation of these imported mirror surfaces. Although parts suppliers indicate that they can obtain aspheric E.U. mirrors, in most cases when attempting to actually place an order, there is a problem. It appears that European manufacturers do not want aspherics on their vehicles in the U.S. because such mirrors do not meet Federal regulations.

Research shows a modest preference for aspheric mirrors over convex and flat mirrors. Moreover, limited accident database analysis suggests a reduced frequency of crashes with aspheric mirrors. There is, however, limited age-related information regarding acceptance and use of aspheric mirrors. It appears that the greater field-of-view afforded by aspheric mirrors is more beneficial than the unit magnification feature of flat mirrors, which have a relatively narrow field-of-view. The main conclusion drawn from this review is that use of aspheric mirrors is worthy of further research examination for both the driver and the passenger side.

## PART II: OPTICAL AND MATHEMATICAL DERIVATIONS AND ANALYSES

A necessary part of understanding rear-view mirrors involves optical and mathematical derivations. Without these, one can only observe what happens when a given type of mirror is used. Fortunately, most derivations can be accomplished using straightforward analyses.

The analyses presented in this part of the report are important because they demonstrate the physical phenomena taking place with the various types of mirrors. These phenomena include image minification, mirror reflectivity, and surface reflectance. In addition, mathematical surface profiles are derived. The analyses have served as part of the basis for experimentation reported later.

# CHAPTER 7: IMAGE MINIFICATION FACTOR FOR CONVEX REAR-VIEW MIRRORS

## Introduction

There is confusion regarding how to calculate the effects of a convex mirror on the rear visual scene as viewed by a typical driver. While simple optical equations are applicable to the problem, it is very important to apply and interpret them correctly. This chapter shows how to use the various equations so that the proper conclusions are drawn.

The major problem is obtaining the correct image size, relative to a flat mirror. Basically, the convex mirror makes the image appear smaller than that obtained with a flat mirror. However, to calculate how much smaller the image appears is not straightforward. The derivation to be shown here uses the approach of an "image minification factor." This is the ratio of image size as it appears with the convex mirror compared with the image size as it appears with a corresponding flat mirror. This ratio, which is always less than unity, provides an indication of how much smaller an image is when the convex mirror is used. The key to obtaining the correct answer for minification is to take into account the angle that the image subtends at the driver's eye.

There are two major steps in the calculations. The first involves obtaining the location of the virtual image and its apparent magnification. These quantities are obtained using straightforward optical equations. However, the magnification, which is less than unity in this case, is *not* the correct factor for reduction in apparent image size. Therefore, a second major step is required, involving determination of the angle subtended at the driver's eye by the image. Once the subtended angles for the convex mirror and for a corresponding flat mirror are obtained, it becomes possible to obtain the correct minification factor. The two steps are shown separately in this report.

## Calculation of Virtual Image Distance and Magnification

Figure 4 shows the typical situation in which a convex rear-view mirror is used. The driver is positioned in front of a convex mirror and looks into the mirror at a typical object such as another vehicle.

The distance between the object and the mirror is defined as $s$, the object distance, and is a positive value. The virtual image as viewed by the driver is on the opposite side of the mirror. The distance from the mirror to the virtual image is defined as $s'$ and is a negative value.

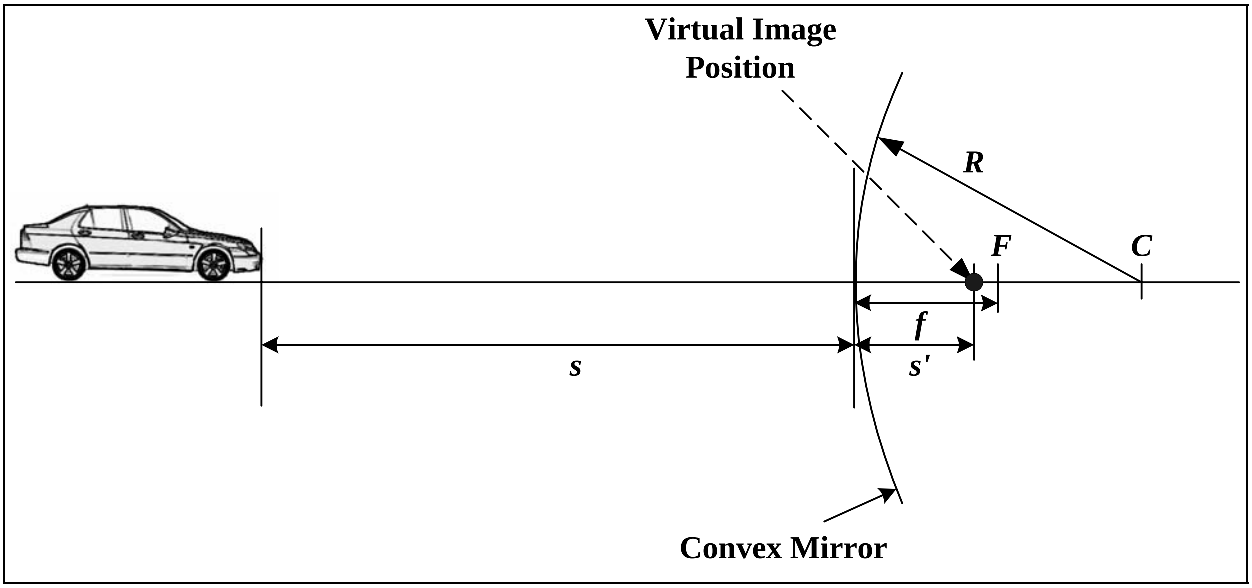


**Figure 4. Convex rear-view mirror cast as an optics problem.**

The mirror is convex and has a constant radius of curvature, *R*. For such a mirror the focal distance, *f*, is given by

$$f = -\frac{R}{2} \tag{1}$$

The focal distance for a convex mirror is always negative; it is located on the back side of the mirror. (The focal distance is measured from the plane of the mirror to the focus position, *F*, as shown in Figure 4.)

To calculate the virtual image distance, *s'*, the following equation is used:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \tag{2}$$

As a typical example, assume a convex mirror with a radius of curvature of 2,000 mm (78.74 in) is used. Assume a vehicle is located 100 ft (30.5 m) away from the convex mirror. Equation (1) indicates that the focal distance for the mirror is -39.37 in (-1.00 m). Then, substituting this value into Equation (2) provides the following result:

$$\frac{1}{s'} = -\frac{1}{39.37} - \frac{1}{1200}$$

$$s' = -38.119 \text{ in} \tag{3}$$

It becomes clear that the virtual image is just to the left of the focus, *F*, in Figure 4. To calculate the magnification factor, the following equation is used:

$$M = \frac{-s'}{s} = \frac{+38.119}{1200} = 0.031767 \quad (4)$$

This factor shows that the virtual image is much smaller than the object. The mistake that is sometimes made is to assume that the convex mirror will yield an *apparent* image size that is reduced by this large factor. Such an assumption can lead to seriously erroneous conclusions because it does not take viewing distance and virtual image distance into account.

### Calculation of the Angles Subtended at the Driver's Eye

The second step in the process of getting the minification factor is to determine the angles subtended at the driver's eye for both the convex mirror and a corresponding flat mirror. Figure 5 depicts the situation.

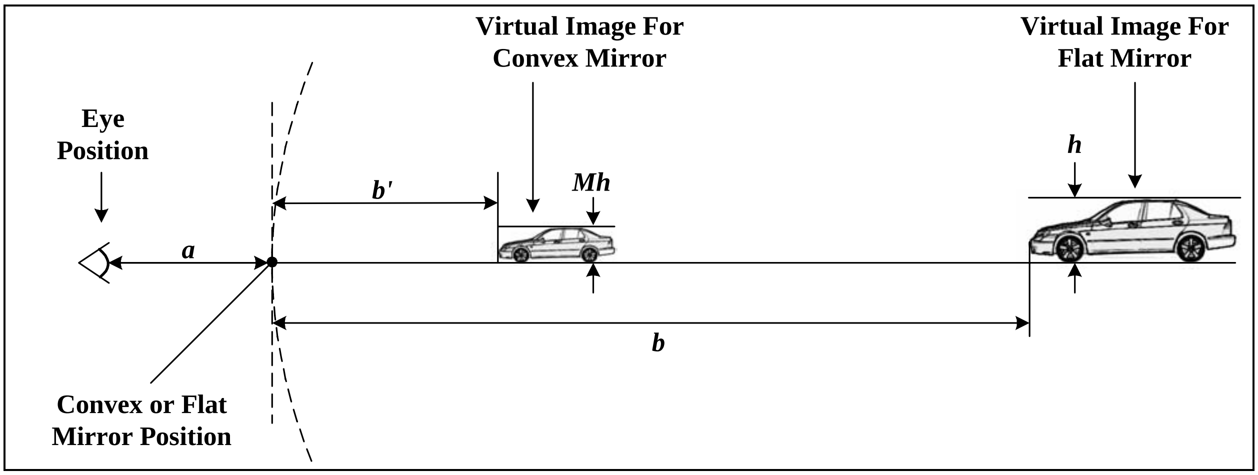


**Figure 5. Diagram for calculating virtual image subtended angles.**

The driver views the image at a distance, *a*, from the mirror, whether it is flat or convex. The distance from the mirror to the virtual image for the convex mirror is *b'*, while the distance from the mirror to the virtual image for the flat mirror is *b*. The height of the virtual image for the convex mirror is *Mh*, and the height of the virtual image for the flat mirror is *h*.

The total image viewing distance for the convex mirror is

$$V_C = a + b' \quad (5)$$

and the total viewing distance for the flat mirror is

$$V_F = a + b \quad (6)$$

Correspondingly, the angle subtended at the eye for the image in the convex mirror is

$$\theta_C = \frac{Mh}{a + b'} \quad (7)$$

and the angle subtended at the eye for the image in the flat mirror is

$$\theta_F = \frac{h}{a+b} \tag{8}$$

The above two equations use small angle approximations and the angles are given in radians.

The ratio of the angle subtended by the convex mirror to the angle subtended by the flat mirror then gives the correct image minification factor

$$\frac{\theta_C}{\theta_F} = \frac{M(a+b)}{(a+b')} \tag{9}$$

In this equation, note that *b'* is the negative of the virtual image distance for the convex mirror, (*b'* = - *s'*), a positive quantity. Note also that *b* is equal to the distance that the object is away from the front of the flat mirror because the mirror has unity gain. Therefore, *b* = *s* and the minification factor becomes

$$\frac{\theta_C}{\theta_F} = M\frac{(a+s)}{(a-s')} \tag{10}$$

To continue the previous example, assume the driver is 36 in (0.91 m) from the mirror for both the convex and the flat mirror cases. Then, substituting the various quantities into the minification factor equation yields

$$\frac{\theta_C}{\theta_F} = 0.031767\frac{36+1200}{36+38.119} = 0.5297 \tag{11}$$

It is immediately apparent that the minification factor is much larger than *M* for the example. The convex mirror reduces the apparent size of the image to approximately half, not by the much smaller value, *M*.

It is possible to write the minification factor in terms of the convex mirror radius of curvature. In so doing, a direct relationship between mirror radius of curvature and the minification factor is obtained. This is accomplished by straightforward substitution and results in the following equation:

$$\frac{\theta_C}{\theta_F} = \frac{R(a+s)}{2as+R(a+s)} \tag{12}$$

Note in this equation that as *R* approaches infinity the minification factor approaches unity, as expected.

Using the earlier numerical example, the minification factor becomes

$$\frac{\theta_C}{\theta_F} = \frac{78.74(36+1200)}{2(1200)(36)+78.74(36+1200)} = 0.5297 \tag{13}$$

which is identical to that obtained previously.

It is also possible to calculate the factor of increase in hypothetical distance using a simple analysis. If it is assumed that the driver judges distance to another vehicle based strictly on familiarity with its size, then apparent distance can be assumed to be proportional to relative height. Using the small angle approximation, height divided by distance equals the subtended angle of the image in radians. If the height remains constant (the vehicle does not change its height), but the distance changes, then the angle subtended is inversely proportional to apparent distance. Accordingly, the apparent distance is given by

$$D = \frac{\theta_F}{\theta_C}(a + s) \quad (14)$$

where $D$ is the apparent distance, $a$ is the distance of the driver to the mirror, and $s$ is the actual distance (that is, the object distance). Note that $D$ is simply the total actual distance divided by the minification factor. In addition, to a first approximation, the apparent distance is increased by the inverse of the minification factor.

For the previous example

$$D = \frac{1}{0.5297}(36 + 1200) = 2333.4 \text{ in; } 194.4 \text{ ft} \quad (15)$$

While the apparent distance equation above suggests that the driver should estimate the distance at nearly twice the object distance, experimentation by other researchers discussed in Part I has shown that drivers do not overestimate by this amount. Instead, much smaller estimates are given. In Part III, the previous results are checked by means of an experiment (Chapter 14 of this current report), which shows results similar to the earlier work.

## Further Analyses and Conclusions

The relationship shown in equation (12) allows the calculation of minification for a convex mirror of a given radius of curvature, object distance, and driver eye distance from the mirror. Since radius of curvature can be measured directly with a precision instrument, the minification factor can then be calculated.

It is instructive to calculate minification factors for typical driver situations. Assume that on the driver side, the distance from the eyes to the mirror is 30 in (0.762 m). Similarly, assume that on the passenger side the distance from the driver's eyes to the mirror is 52 in (1.32 m), and also assume an object distance of 100 ft (30.5 m). Under these conditions, it is possible to calculate the minification factor as a function of the convex mirror radius of curvature. The plot in Figure 6 shows the results for radii of curvature from 500 mm (19.68 in) to 10,000 mm (393.7 in) for a flat mirror ($R = \infty$). In the figure the abscissa is logarithmic, showing that the radius of curvature of a convex mirror must be increased at greater rates to achieve approximately equal increases in minification factor. The graph also shows that the passenger-side mirror creates a greater degree of minification than the driver-side mirror for a given radius of curvature. This is a result of the greater viewing distance for the passenger-side mirror. Clearly, a convex mirror installed on the driver side will have somewhat different viewing characteristics compared to the same mirror installed on the passenger side.

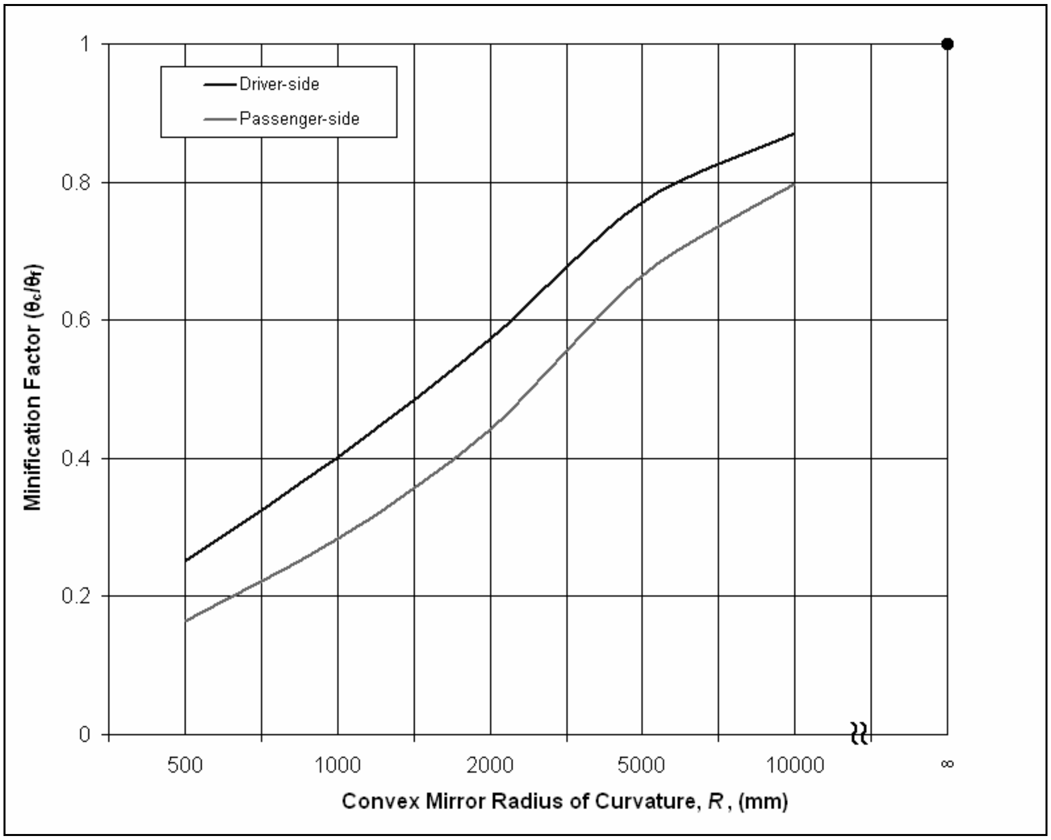


**Figure 6. Plot of minification factor as a function of convex mirror radius of curvature, for driver-side and passenger-side examples.**

The results of the analysis contained in this chapter show that care must be taken in computing the image minification factor and that virtual image magnification alone will not provide the correct answer. Equation 12 and its application, as exemplified in Figure 6, provide correct answers for this problem and should be used.

# CHAPTER 8: CALCULATION OF REFLECTIVITY FOR CONVEX MIRRORS

## Introduction

Reflectivity in convex mirrors is an important property. It determines the "brightness" of objects as they appear in the mirror. Reflectivity is important for two reasons: first, it is a factor in determining how easily objects can be detected and identified in subdued light, and second, it plays an important role in reflected glare. Regarding the second reason, all rear-view mirrors produce reflected headlight glare at night. Convex mirrors, because they have a greater area of coverage than corresponding flat mirrors, will pick up headlight glare from a larger area. Questions regarding glare must therefore be answered.

## Analysis

Platzer (1995) provided equations for reflectivity of flat and convex mirrors. His equations are re-cast here in terms of parameters defined in Chapter 7 of the current report. Doing so provides a consistent presentation.

The reflected illuminance for a flat mirror is given by

$$r_F = \frac{\rho_F I_S}{(a+s)^2} \tag{16}$$

where $\rho_F$ is the reflectance of the surface material of the flat mirror, $I_S$ is the luminous intensity of the glare source, $a$ is the distance from the driver to the mirror, and $s$ is the distance of the glare source to the mirror (the object distance)[1]. Note that this equation is simply the luminous intensity of the source divided by the square of the total distance with the result multiplied by the surface material reflectance. The equation is straightforward because luminous intensity falls off as the inverse square of distance.

The reflected illuminance for a convex mirror is more complicated and is given by

$$r_C = \frac{\rho_C I_S}{\left(\frac{2as}{R} + a + s\right)^2} \tag{17}$$

where $\rho_C$ is the reflectance of the surface material of the convex mirror, $R$ is the radius of curvature of the convex mirror, and the other parameters are as defined previously.
The ratio of the reflected illuminances then becomes

$$\frac{r_C}{r_F} = \frac{\rho_C (a+s)^2}{\rho_F \left(\frac{2as}{R} + a + s\right)^2} = \frac{\rho_C R^2 (a+s)^2}{\rho_F \left[2as + R(a+s)\right]^2} \tag{18}$$

However, on recognizing the minification factor of Equation 12 in Chapter 7, this ratio becomes

[1] In the current report, the word "reflectance" is used to describe reflecting properties of surfaces (that is, the silvering of the surface). The word "reflectivity" is used to describe reflecting properties of mirrors including their curvature.

$$\frac{r_C}{r_F} = \frac{\rho_C}{\rho_F}\left(\frac{\theta_C}{\theta_F}\right)^2 \tag{19}$$

Clearly, the effect of substituting a convex mirror for a flat mirror is to reduce the reflected illuminance by the square of the minification factor, assuming the reflectances of the surface materials are the same for the two mirrors. This will have the effect of reducing glare, but this "improvement" must be traded off against the fact that more glare sources are likely to be reflected into the driver's eyes.

If the surface material treatments (for the flat and the convex mirror) differ, then the difference in mirror surface reflectances can be included in $\rho_C$ and $\rho_F$ in Equation 19 above.

What is occurring with convex mirrors to cause the reflectivity to be smaller than that of the corresponding flat mirror? There is a simple, intuitive way to look at this problem to understand what is happening. Consider that there is a flat, but flexible mirror. If the driver looks into this mirror, a certain amount of light will be reflected from the source into the driver's eyes. Now if the flexible mirror is forced into a convex shape, the light from the source will be reflected back over a larger area. In other words, light becomes more spread out after reflection. Therefore, light entering the pupils of the driver's eyes must be attenuated somewhat, since it too would be spread over a greater area. Equations 18 and 19 describe this phenomenon mathematically.

## CHAPTER 9: A PRACTICAL METHOD FOR OBTAINING MIRROR PARAMETERS

### Introduction

This chapter sets out the method used to obtain mirror parameters. It provides a straightforward method for measuring convex mirror radius of curvature and surface material reflectance. These parameters are needed for comparison.

### Determining Convex Mirror Radius of Curvature

Convex mirror radius of curvature can be obtained by direct geometric measurement with a precision instrument. This instrument has two fixed points and a relative measuring point centered between the fixed points, as shown in Figure 7. The center value is adjusted to zero on the dial indicator using a flat surface prior to mirror measurement. The surface should be a precision flat surface with a variability of not more than 0.0001 in (0.0025 mm). The device is then placed over the mirror and measures the offset, $h_0$, created by the convex mirror.

**Figure 7. Precision instrument for measurement of convex mirror radius of curvature.**

The geometry corresponding to the measurement is shown in Figure 8. In the figure, the offset measurement, $h_0$, is obtained using the instrument, and $d_0$ is one-half the total distance between the two fixed points of the instrument. $R$ is the radius of curvature of the convex mirror.

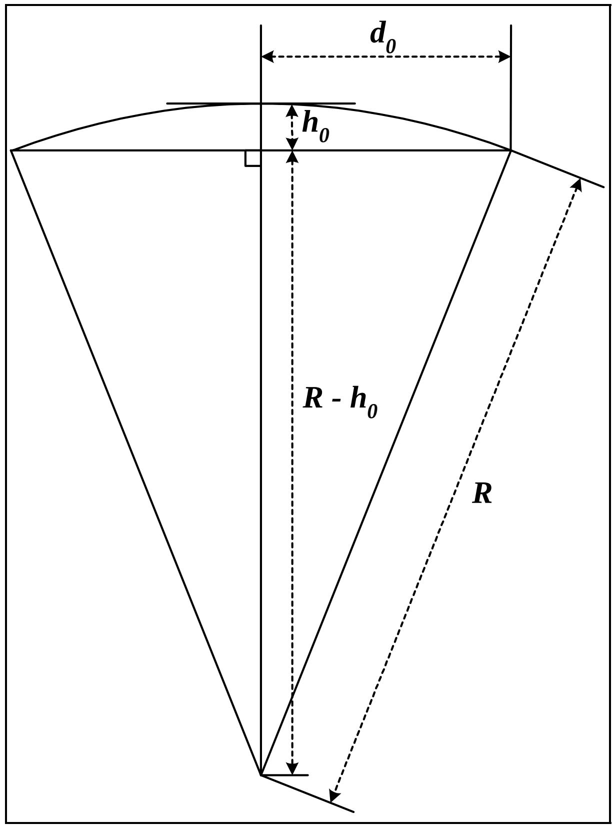


**Figure 8. Geometry associated with the measurement of radius of curvature.**

The Pythagorean Theorem for the right triangle in the figure yields

$$R^2 = d_0{}^2 + (R - h_0)^2 \tag{20}$$

which simplifies to

$$R = \frac{d_0{}^2 + h_0{}^2}{2h_0} \tag{21}$$

Consequently, the offset and the distance from center to one fixed pointer are sufficient to provide the convex mirror radius of curvature. This is a straightforward calculation, but of course all values should be in the same units of measure**.**

As an example, a mirror is found to have an offset of 0.0175 in (0.4445 mm). The measurement apparatus has a fixed point distance, $d_0$, of 43 mm. If the radius of curvature is desired in millimeters, the calculation yields

$$R = \frac{(43)^2 + (0.4445)^2}{2(0.4445)} = 2080\,\text{mm} \tag{22}$$

**Measurement of Flat Mirror Surface Material Reflectance**

A flat mirror has an image minification factor of unity and therefore the surface material reflectance, $\rho_F$, and the mirror reflectivity, $r_F$, have the same value. To obtain this value, an apparatus like that shown in Figure 9 is set up. The flat mirror is considered first.

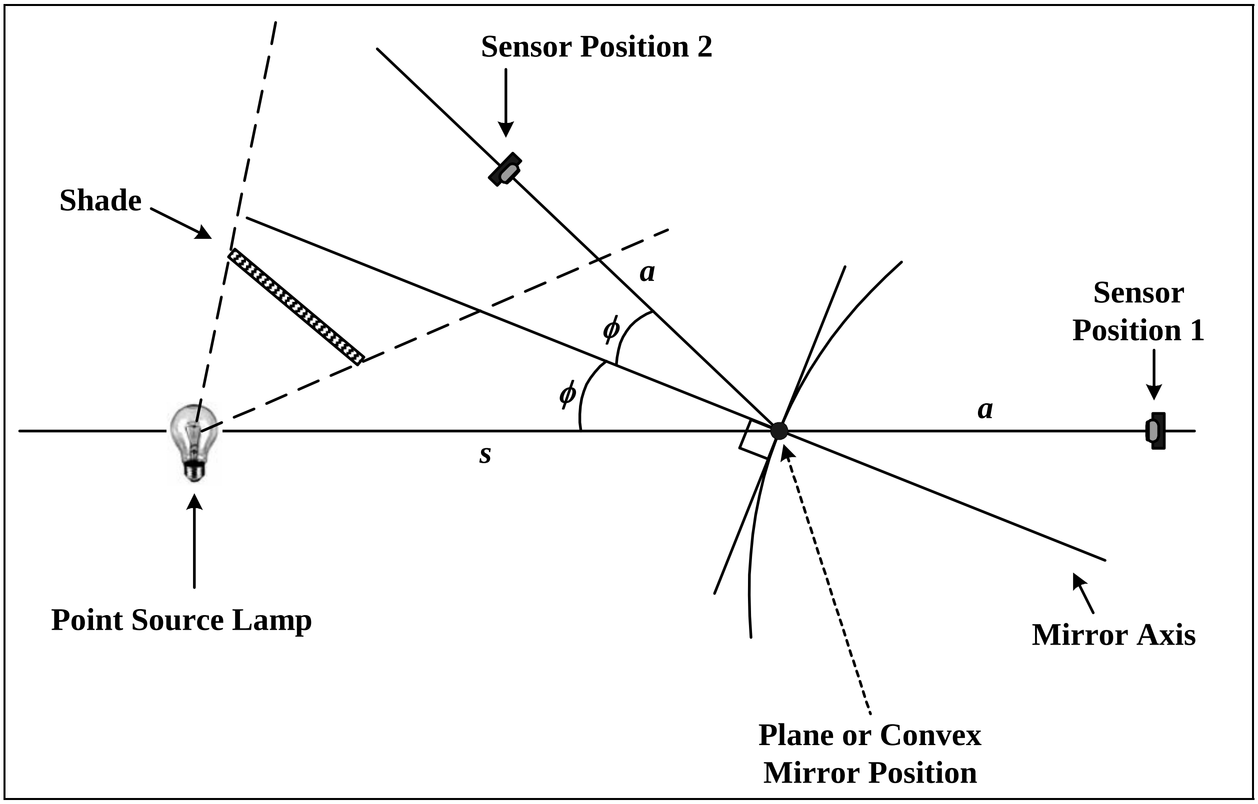


**Figure 9. Apparatus for use in determining relative reflectivity.**

A point source of light is placed so that the sensor in Position 1 can measure the illuminance, $L_0$, with the flat mirror removed. Then the flat mirror is placed in the optical path, the sensor is moved to Position 2, and the illuminance created by the flat mirror, $L_F$, is measured. Care must be taken to ensure that light from the point source does not directly enter the sensor in Position 2. Figure 9 shows a shade used for this purpose. Note that the sensor in Positions 1 and 2 has the same optical distance from the point source, namely, $s + a$. Under these conditions the surface material reflectance of the flat mirror, $\rho_F$, is given by the reading in Position 2 divided by the reading in Position 1, that is:

$$\rho_F = \frac{L_F}{L_0} \tag{23}$$

### Measurement of Surface Material Reflectance for a Convex Mirror

For the convex mirror case, measurement of surface material reflectance is more complicated because of the curvature of the surface. Correction must be made for this curvature to avoid errors. Returning to Figure 9, the same measurement procedures are used. The convex mirror is first removed and the measurement, $L_0$, is made at Position 1. Thereafter, the convex mirror is inserted in the optical path and the measurement, $L_c$, is made at Position 2. However, additional computations must be performed.

Note that the illumination at the Sensor Position 2 will be diminished by two factors: the surface material reflectance, $\rho_c$; and the fact that the light is spread more widely by the convex mirror (as described previously in Chapter 8). It is the second factor that must now be taken into account.

Equation 17 of Chapter 8 provides the reflectivity for a convex mirror. If this convex mirror were "flattened" to form a flat mirror, the resulting flat mirror would have the reflectivity given by this same equation but with $R = \infty$. The ratio of reflectivities of these two mirrors would then be given by

$$\frac{r_{cFLAT}}{r_c} = \frac{\dfrac{\rho_c I_s}{(a+s)^2}}{\dfrac{\rho_c I_s}{\left(\dfrac{2as}{R}+a+s\right)^2}} = \frac{\left(\dfrac{2as}{R}+a+s\right)^2}{(a+s)^2} \tag{24}$$

Since the "flattened" mirror would have a higher reflectivity, the ratio shown in Equation 24 will be greater than unity. Equation 24 provides the correction factor that is needed to obtain the surface material reflectance of the convex mirror. The surface material reflectance of a convex mirror is then given by

$$\rho_c = \frac{L_c\left(\dfrac{2as}{R}+a+s\right)^2}{L_0(a+s)^2} \tag{25}$$

As an example, assume that the ratio of measured illuminances is $Lc/L_0 = 0.35$.
Assume that $s$, the distance of the mirror to the source, is 1,000 mm and that $a$, the distance from the mirror to the sensor, is 500 mm. Assume further that the radius of curvature of the convex mirror is 2,000 mm. Then the surface material reflectance of the convex mirror becomes

$$\rho_c = \frac{0.35\left(\dfrac{2\cdot 500\cdot 1000}{2000}+500+1000\right)^2}{(500+1000)^2} = 0.622 \tag{26}$$

The surface material reflectance is larger than the ratio of measured illuminances, as expected.

Finally, it should be noted that the ratio of "apparent brightness" for a convex mirror with surface material reflectance of $\rho_c$ relative to a flat mirror with surface material reflectance of $\rho_F$ is given by Equation 19 of Chapter 8. But, this ratio is also given by $L_c$ divided by $L_F$. Thus, the ratio of illuminance measurements provides an indication of the relative brightness of objects in a convex mirror with arbitrary surface material reflectance, $\rho_c$, compared with a flat mirror with arbitrary surface reflectance, $\rho_F$, as shown in the following equation:

$$\frac{r_c}{r_F} = \frac{L_c}{L_F} = \frac{\rho_c}{\rho_F}\left(\frac{\theta_c}{\theta_F}\right)^2 = \frac{\rho_c R^2 (a+s)^2}{\rho_F\,[2as + R(a+s)]^2} \tag{27}$$

## Summary

A general procedure has now been developed for obtaining the main parameters of a convex mirror. The steps are as follows:

1. Obtain the radius of curvature, $R$, of the convex mirror using a measurement instrument as shown in Figure 7 and the geometry shown in Figure 8 of this chapter. Calculate the radius using Equation 21 of this chapter.
2. Using the apparatus shown in Figure 9 and Equation 25 of this chapter, calculate $\rho_c$, the surface material reflectance of the convex mirror.
3. For a given application, determine the distance that the driver is from the mirror, $a$, and the distance that the object is from the mirror, $s$, as described in Chapter 8. Then use Equation 12 of Chapter 7 to determine the image minification factor.
4. For the same application, calculate the apparent distance, D, that the object is away from the driver, using Equation 14 of Chapter 7. (Note that this is the apparent distance based on angle subtended at the eye and may differ somewhat from driver *perception* of distance.)
5. To calculate the "relative brightness" of an object (actually, the relative reflected illuminance) seen in the convex mirror compared with the same object seen in an arbitrary flat mirror at the same location, determine $L_c$ using the apparatus in Figure 9 of this chapter with exactly the same point source as that used to obtain $L_F$. Then the relative brightness will be given by the ratio $L_c/L_F$. It is also given by Equation 19 of Chapter 8.
6. If desired, the focal distance, $f$, the virtual image distance, $s'$, and the magnification, $M$, of the convex mirror can be calculated for the given application using Equations 1, 2, and 4, respectively, of Chapter 7.

# CHAPTER 10. ASSESSMENT OF THE LOOMING EFFECT OF CONVEX MIRRORS

## Introduction

Platzer (1995) demonstrated that the minification factor associated with convex mirrors is a function of object distance. In particular, he showed that as an object approaches the mirror, its size becomes larger more quickly. This nonlinearity would seem to create two distortions: a "looming" effect in which the image would appear to become larger more quickly, and correspondingly an apparent increase in velocity. In Platzer's words, "As a car approaches, it appears to increase in size at a faster rate than would a car in a plane mirror." However, he used an object distance range of zero to 25 ft (7.62 m). Clearly, the zero distance almost never occurs in practice, because it would involve the object colliding with the mirror. Furthermore, very short distances are irrelevant because the object vehicle would then already be alongside. Consequently, minification as a function of distance was re-examined with the idea of determining how much of an effect the nonlinearity has for more realistic distances.

As derived earlier in this report (Chapter 7), the relationship between minification and object distance is

$$\frac{\theta_C}{\theta_F} = \frac{R(a+s)}{2as + R(a+s)} \tag{28}$$

In this equation, *R* is the radius of curvature of the mirror, *a* is the distance from the observer's eyes to the mirror, and *s* is the object distance, that is, the distance from the mirror to the object.

## Driver-side Analysis

For a typical situation, the driver-side rear-view mirror would be approximately 30 in (0.762 m) from the driver's eyes, and typical convex mirrors (that might possibly serve as candidates for use) would have radii of curvature of 2,000 mm (78.74 in) and 1,400 mm (55.12 in). Drivers would most likely use these mirrors for object distances of 10 to 200 ft (3.05 to 61.0 m). Using the above equation, the minification factor was calculated for each of the two mirror radii across the object distances. The results are plotted in Figure 10. The figure clearly shows that there is minor nonlinearity in the minification factor. In particular, this occurs near the 10 ft (3.05 m) distance. However, at this distance an object vehicle would already be alongside the observer's (driver's) vehicle.

The results of the analysis indicate that for distances beyond 10 ft. (3.05 m), there is very little change in the minification factor, and therefore, from the driver's standpoint, there is no substantial looming or nonlinear effect. It is only when object distances are nearer than 10 ft (3.05 m) that appreciable looming and nonlinearity occur. Clearly, the driver would not be attempting to estimate distance and closing speed for a vehicle that is already alongside.

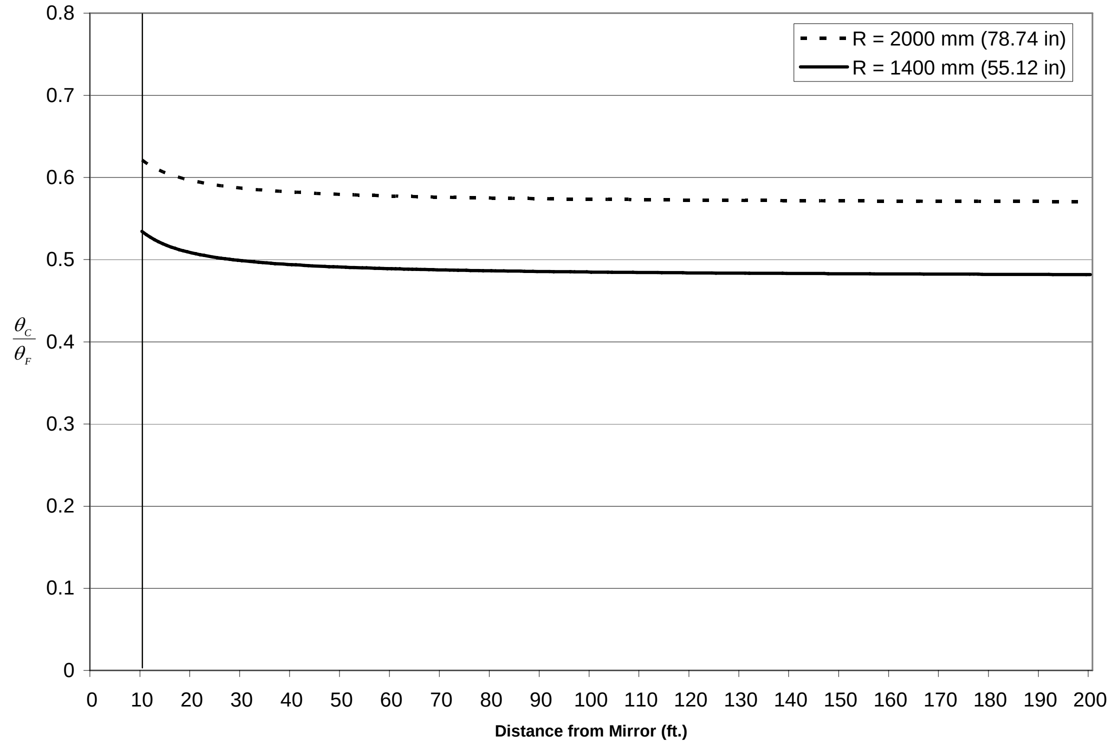


**Figure 10: Minification factor as a function of object distance for typical candidate convex mirrors (on the driver side of the vehicle).**

### Passenger-side Analysis

There is only one change necessary for assessing the effect of nonlinearity on the passenger side, namely, the value of $a$, the distance from the driver's eyes to the mirror. For this case, a typical value would be 52 in (1.32 m). However, there is also a possibility that a mirror with a slightly smaller radius of curvature might be used on the passenger side. Thus, the radii used for the computations are 2,000 mm (78.74 in), 1,400 mm (55.12 in), and 1,200 mm (47.27 in). Substituting into the minification equation and using the same range of distances, that is, 10 to 200 ft (3.05 to 61.0 m), results were obtained for the three different mirrors. They are plotted in Figure 11.

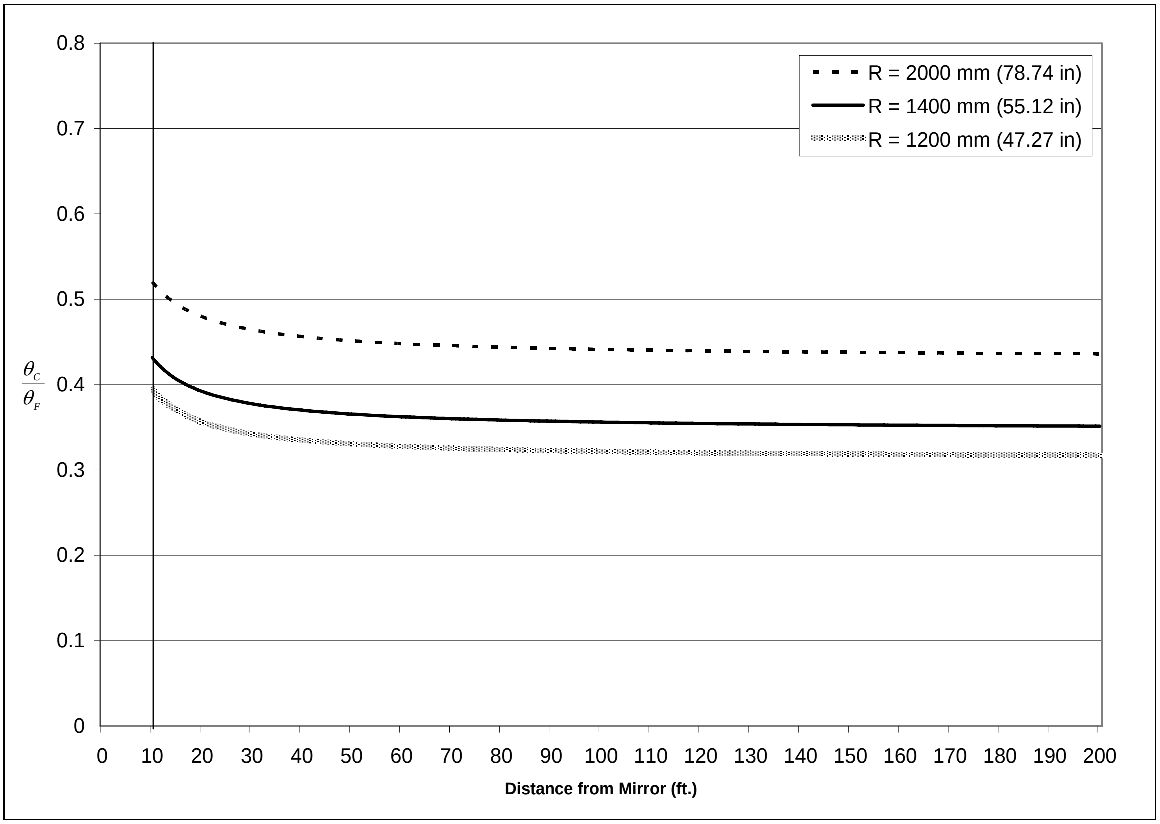


**Figure 11: Minification factor as a function of object distance for typical convex mirrors (on the passenger side of the vehicle).**

The figure shows that there is more nonlinearity for the passenger-side mirror. The minification now shows increases of 19.3 percent, 23.1 percent, and 24.3 percent from 200 ft down to 10 ft (61 m down to 3.05 m) for the 2,000, 1,400, and 1,200 mm mirrors, respectively. These values might be noticeable to the driver, thus creating a mild looming effect. However, the most rapid change is in the last 10 ft (3.05 m). The increases in minification from 200 ft down to 20 ft (61 m down to 6.1 m) are 9.9 percent, 11.7 percent, and 12.3 percent, that is, roughly half the total increase. Most likely, the driver would not notice looming for any situation in which the object is 20 ft (6.1 m) or more from the mirror. It is only when the object is inside this range that looming might be noticeable.

### Overall Effect of the Nonlinearity

On the driver side, the most important finding is that the nonlinearity associated with convex mirrors is not appreciable in the range where mirror use for distance and closing speed estimation might occur. It is most likely that the driver would not notice any looming or accelerating effect resulting from the nonlinearity in minification during critical closing distances.

On the passenger side, there is slightly more nonlinearity. This might be noticeable by the driver for closing distances between 10 and 20 ft (3.05 and 6.1 m) from the mirror. However, beyond

20 ft the amount of change in minification is relatively small, suggesting once again that the driver would not notice the nonlinearity.

In summary, it is probably safe to say that looming would not be noticeable on the driver side for objects more than 10 ft (3.05 m) away from the mirror and on the passenger side for objects more than 20 ft (6.1 m) away from the mirror. Thus, the nonlinearity should not play a major role at distances where the driver might be attempting to estimate distance and closing speed, that is, beyond 20 ft (6.1 m) from the corresponding mirror. It is also important to mention that, since there is slightly less minification (slightly more magnification) as the object approaches, the small nonlinearity that does exist would produce conservative, that is, safe estimates. In other words, actual object distance would be larger than apparent object distance, and actual object closing speed would be lower that apparent closing speed. These statements assume that the driver is referenced to the minification level associated with larger distances.

# CHAPTER 11: DEVELOPMENT OF EQUATIONS DESCRIBING ASPHERIC REAR-VIEW MIRRORS AND MEASUREMENT OF ASPHERIC MIRROR PARAMETERS

## Introduction

Previous derivations have dealt primarily with spherical and flat mirrors. However, it is also necessary to be able to specify and deal with aspheric mirrors. Doing so represents a substantial complication because such mirrors use a compound curve that must be described mathematically. The main objective is to be able to describe aspheric mirrors accurately and with as few parameters as possible.

In the early development of compound mirrors (i.e., mirrors that were neither flat nor spherical), Pilhall (1981) investigated a variety of approaches. His recommendation after completing his work was a "Type 4" mirror. The inner portion was spherical and the outer portion was a compound curve in which the instantaneous radius of curvature in the horizontal dimension decreased with distance from the inner edge. In other words, there was greater horizontal curvature toward the outside of the mirror. In the vertical dimension, the radius of curvature of the spherical portion was maintained. While such a mirror produced horizontal distortion of reflected images in its outer portion, it also gave a greater field-of-view.

Pilhall's "Type 4" concept is the one that is now being used for aspheric mirrors in the European Union. Consequently, his description will be used here as the starting point. Various elements are supplemented in this development to make the presentation clearer and more adaptable to direct measurement. In addition, reflectivity considerations are included.

## Fundamental Development

The equation used to describe the horizontal profile of an aspheric mirror can be written as a combination of a circle and a cubic as follows:

$$y = \begin{cases} R_c - \left(R_c^{\,2} - x^2\right)^{1/2} & ; x \le d_1 \\ R_c - \left(R_c^{\,2} - x^2\right)^{1/2} + k\left(x - d_1\right)^3 & ; x > d_1 \end{cases} \tag{29}$$

In this equation $R_c$ is the (constant) radius of curvature of the inner (spherical) portion of the mirror, $x$ and $y$ are the coordinates of the surface of the mirror, $d_1$ is the delineator between the spherical and aspheric portions of the mirror, and $k$ is a constant used to obtain the desired value of additional curvature contributed by the cubic in the aspheric portion.

The equation uses the coordinate system shown in Figure 12. The center of the spherical portion of the mirror is located on the $y$-axis. The inner edge of the mirror is located at the origin and is tangent to the $x$-axis, as shown. At $x = d_1$, the mirror changes to an aspheric with the instantaneous radius of curvature, $R$, decreasing. The overall mirror outside edge is located on the line $x = d_2$. Figure 12 shows these geometric aspects with the curvature expanded for clarity. Under normal conditions the *observable* curvature of the mirror would be far less than that shown in Figure 12, which has an expanded y axis.

To obtain the instantaneous horizontal radius of curvature for the aspheric portion of the mirror, it is first necessary to find the first and second derivatives of that portion. They are obtained by differential calculus.

$$\frac{dy}{dx} = \frac{x}{\left(R_c^{\ 2} - x^2\right)^{1/2}} + 3k\left(x - d_1\right)^2 \tag{30}$$

$$\frac{d^2y}{dx^2} = \frac{R_c^{\ 2}}{\left(R_c^{\ 2} - x^2\right)^{3/2}} + 6k\left(x - d_1\right) \tag{31}$$

The horizontal instantaneous radius of curvature of the aspheric portion is also given by differential calculus as

$$R = \frac{\left[1 + \left(\frac{dy}{dx}\right)^2\right]^{3/2}}{\left|\frac{d^2y}{dx^2}\right|} \tag{32}$$

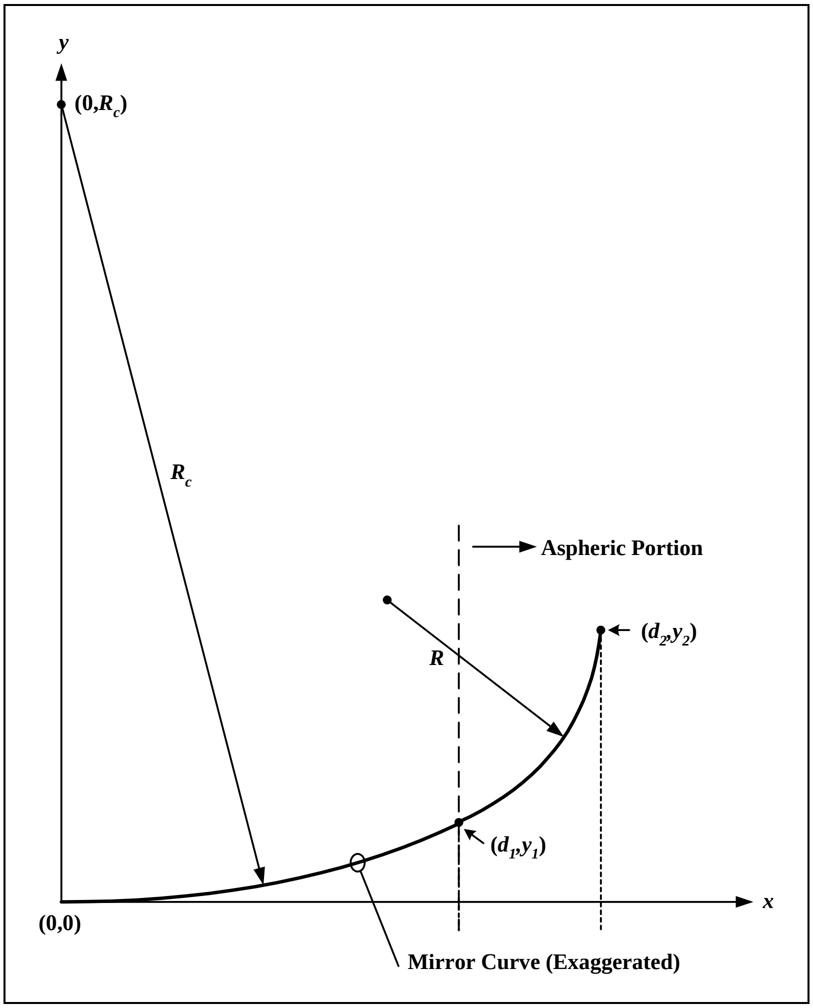


**Figure 12. Coordinate system for the aspheric mirror derivations.**

To use Equation 32, it is probably easiest to solve for $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$ at various points along the x-axis and then substitute the values into the Equation 32.

An additional equation that will be needed is the equation for the tangent angle at the outside edge of the mirror, $\theta_E$, which is given by

$$\theta_E = \arctan\left(\frac{dy}{dx}\right)\Bigg|_{x=d_2} \tag{33}$$

Note that $\theta_E$ is the total (acute) angular difference between the outside and inside edges of the mirror.

### Reflectivity of an Image in the Aspheric Portion of the Mirror

The reflectivity of a bright object appearing in the aspheric portion of the mirror will be diminished to a greater extent than an object appearing in the convex portion. This is a result of the fact that the horizontal profile has a greater degree of curvature than does the horizontal profile of the convex portion. This difference will cause the reflected light to be spread over a greater angle, making the light entering the driver's eye smaller in magnitude.

In certain cases, it may be desirable to calculate the reflectivity (for the aspheric portion) relative to a flat mirror. The previous chapters have already shown how to calculate the reflectivity for the spherical portion.

First, it must be recognized that in the aspheric portion, the driver's two eyes see the reflected image at slightly different points on the aspheric mirror. Consequently, a value of *R* should be calculated that represents the approximate average associated with the two eyes. This value will be dependent on the specific geometry of the driver's eye positions, the mirror aim, and the object position. Once this value of *R* is obtained, it becomes possible to calculate the reflectivity.

Equation 27 of Chapter 9 shows that the reflectivity for a *convex* mirror is diminished by the square of the minification factor when compared to a flat mirror. If it is recognized that the horizontal dimension of the aspheric mirror has increasing curvature while the vertical dimension has constant curvature equivalent to that of the spherical portion of the mirror, then the reflectivity can be written as

$$\frac{r_a}{r_F} = \frac{L_a}{L_F} = \frac{\rho_a}{\rho_F}\left(\frac{\theta_{aH}\theta_{aV}}{\theta_F^{\ 2}}\right) = \frac{\rho_a R_H R_V (a+s)^2}{\rho_F \left[2as + R_H (a+s)\right]\left[2as + R_V (a+s)\right]} \tag{34}$$

In this equation, terms previously defined for Equation 27 of Chapter 9 are the same.
In addition, $r_a$ is the reflectivity for the specific point on the horizontal axis of the aspheric mirror, $L_a$ is the reflected illuminance measured for the specific point, $\rho_a$ is the surface material reflectance of the aspheric portion, $\frac{\theta_{aH}}{\theta_F}$ is the horizontal minification factor, and $\frac{\theta_{aV}}{\theta_F}$ is the vertical minification factor. Finally, $R_H$ is the instantaneous horizontal radius of curvature and $R_V$ is the vertical radius of curvature. Generally speaking, $R_V = R_c$, because the vertical radius of curvature is constant across the entire mirror. In addition, if the surface material reflectance does not change between the convex and aspheric portions of the mirror, then $\rho_a = \rho_c$.

Figure 9 of Chapter 9 shows apparatus for obtaining relative reflectivity. This apparatus can be used to obtain relative reflectivity for the aspheric portion, provided that the point of reflection on the mirror corresponds to the point from which the driver views an object, as previously explained.

**Numerical Examples**

Numerical examples using realistic parameters will help to solidify the concepts. The specified parameters are as follows:
$R_c$ = 2,000 mm (78.7 in) radius of curvature of the spherical portion
$d_1$ = 116 mm ( 4.6 in) projected width of the spherical portion
$d_2$ = 180 mm (7.1 in) projected overall width of the mirror
$k$ = 2 x $10^{-5}$ (dimensionless constant)
For these parameters the equation for the horizontal profile of the mirror becomes

$$y = \begin{cases} 2000 - \left(2000^2 - x^2\right)^{1/2} & ; 0 \le x \le 116 \\ \\ 2000 - \left(2000^2 - x^2\right)^{1/2} + 2 \cdot 10^{-5}\left(x - 116\right)^3 & ; 116 < x \le 180 \end{cases} \qquad (35)$$

A plot using an expanded $y$-axis scale is shown in Figure 13. Note that even with the expanded scale the discontinuity at $x$ = 116 is not observable. This corresponds to the fact that the aspheric portion (the cubic in Equation 35) has a second derivative equal to zero at $x$ = 116. Thus, it is unlikely that an image would appear discontinuous to a driver using the mirror (refer back to Figure 2 for examples).

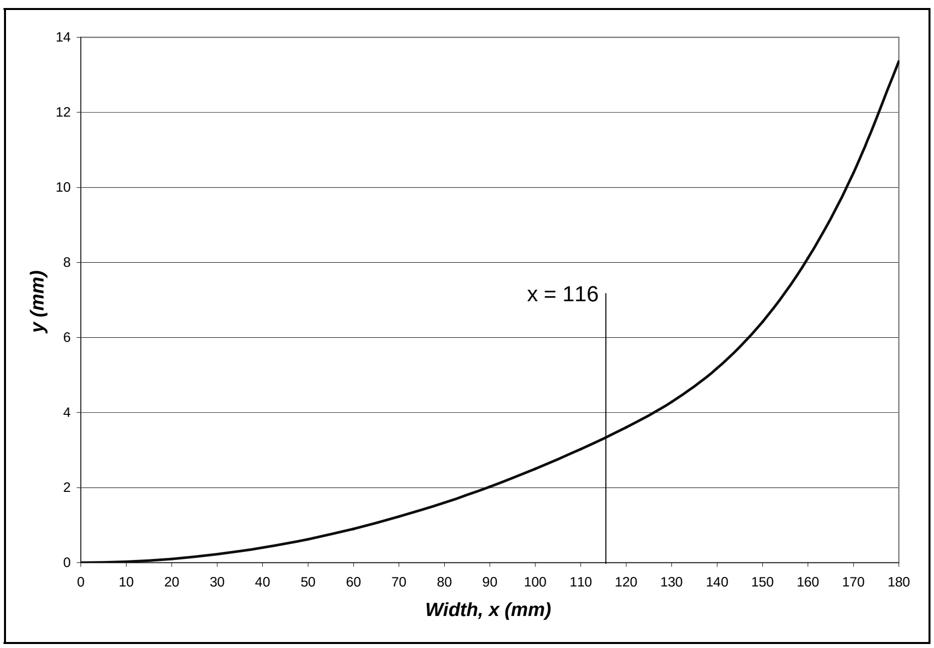


**Figure 13. Plot of the mirror curve (horizontal profile).**

To determine the angular difference between the inner and outer edges of the mirror, the first derivative is evaluated at the outside edge, yielding

$$\left.\frac{dy}{dx}\right|_{x=180} = \frac{x}{\left(2000^2 - x^2\right)^{1/2}} + 3\left(2\cdot 10^{-5}\right)\left(x-116\right)^2 \Big|_{x=180} = 0.336 \tag{36}$$

Correspondingly, the angular difference becomes

$$\theta_E = \arctan\left(\frac{dy}{dx}\right)\Big|_{x=180} = 18.6° \tag{37}$$

To compute the instantaneous radius of curvature in the aspheric portion, both the first and second derivatives are evaluated at various points. The first derivative is given by Equation 36 above, but with x set at various values. The second derivative is

$$\frac{d^2y}{dx^2} = \frac{2000^2}{\left(2000^2 - x^2\right)^{3/2}} + 6\left(2\cdot 10^{-5}\right)\left(x-116\right) \tag{38}$$

Then, substituting the first and second derivative values into Equation 32 for $116 \leq x \leq 180$, the instantaneous radius of curvature is obtained. Below 116, the radius is constant, as previously described. The results are plotted in Figure 14. Although the mirror radius of curvature drops off very sharply, as shown in Figure 14, the mirror contour itself (Figure 13) appears continuous, as previously mentioned.

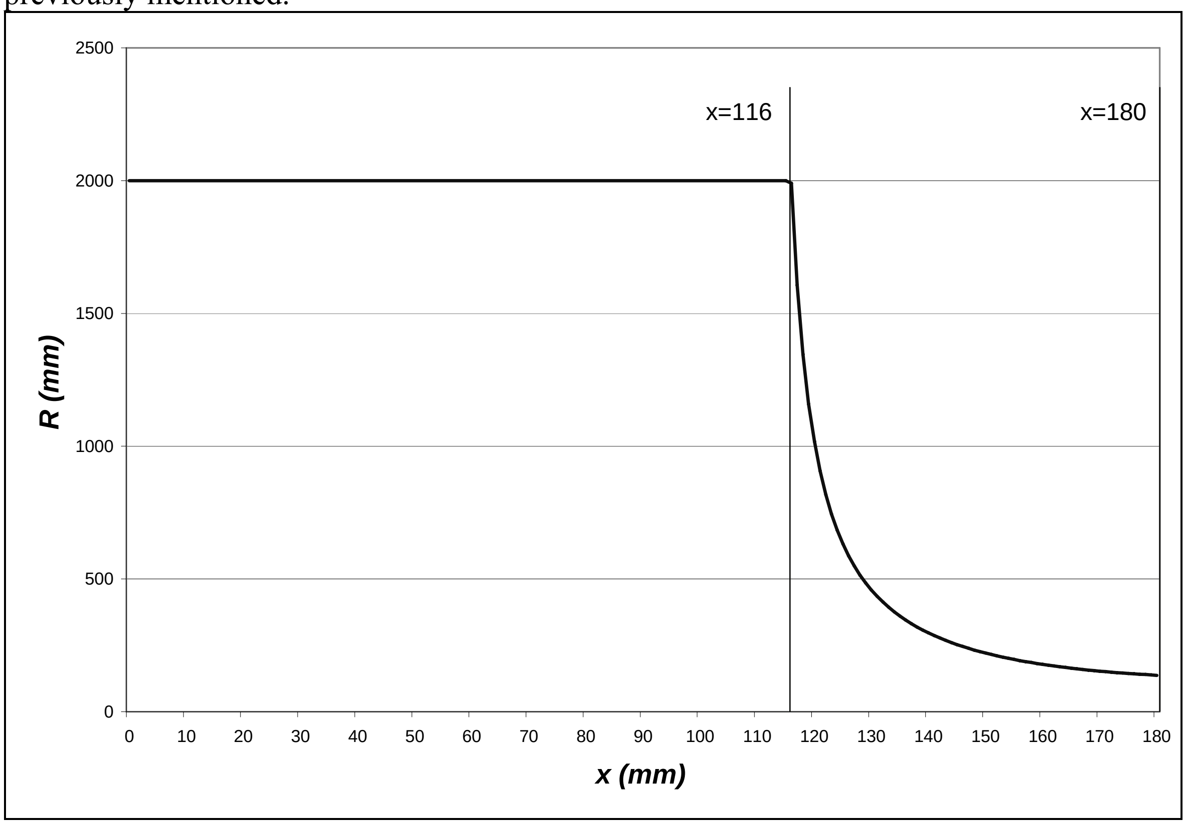


**Figure 14. Plot of the instantaneous radius of curvature for the mirror example.**

As an additional numerical example, assume that the relative reflectivity at $x$ = 160 is desired. This is a point in the aspheric portion of the mirror. Assume that the surface material reflectance of the aspheric portion is the same as that of the comparison flat mirror, that is, $\rho_a = \rho_F$. Assume the same parameters are used as in Chapter 9, namely, $a$ = 500 mm, $s$ = 1,000 mm and $R_c$ = 2,000. At $x$ = 160, the radius of curvature equation yields $R$ = 183.0 mm (as can be observed in Figure 14). Then the equation for relative reflectivity becomes

$$\left.\frac{r_a}{r_F}\right|_{x=160} = \frac{(183)(2000)(500+1000)^2}{[2\cdot 500\cdot 1000+183(500+1000)][2\cdot 500\cdot 1000+2000(500+1000)]} = 0.162 \tag{39}$$

This example shows that the reflectivity is heavily influenced by the additional curvature of the aspheric portion, as expected. The reflectivity is much smaller than for the convex portion of the mirror.

**Obtaining Aspheric Mirror Parameters From Measurements**

The previous presentation allows a set of aspheric mirror parameters to be obtained from a small number of measurements that can be taken directly from the mirror. The steps are as follows:

1. Using an instrument like that shown in Figure 7 of Chapter 9, determine the offset, $h_0$, of the spherical portion of the mirror and then calculate the radius of curvature using Equation 2 of Chapter 9. Note that $R = R_c$, the constant radius of curvature for the spherical portion of the mirror.
2. Measure the width of the spherical portion, $d_1$, and the width of the entire mirror, $d_2$. Note that these measurements should be made with the linear scale tangent to the inside edge of the mirror. This will require a small projection to the surface of the mirror.
3. Measure the angular difference between the (geometric) tangents at the inner and outer edges of the mirror. This value, which is $\theta_{E,}$ is usually 20 deg or less. Take the (trigonometric) tangent of this angle to obtain the first derivative of the mirror at $x = d_2$.
4. Use the first derivative equation (Equation 30), evaluated at $d_2$ to obtain the constant $k$ for the aspheric portion of the mirror. Note that $k$ is the only unknown and is easily obtained, since it appears linearly.
5. The equation for the entire mirror can then be written using Equation 29. Thereafter, the mirror profile can be plotted.
6. The first and second derivatives can then be calculated at various points in the aspheric portion using Equations 30 and 31. Then, using Equation 32, the instantaneous radius of curvature can be plotted.

Note that in the above, there are only four parameters that need to be measured at the mirror: $h_0$, the offset; $d_1$, the width of the spherical portion; $d_2$, the width of the entire mirror; and $\theta_E$, the angular difference across the entire mirror. Consequently, these parameters can be measured with the mirror remaining installed on the vehicle. Thus, the procedure can be used for survey work, if desired.

If reflectance or reflectivity of the aspheric portion is desired, the mirror will probably need to be dismounted and tested. The best procedure involves covering the aspheric portion and making measurements of the spherical portion using the procedure described in Chapter 9. Once the surface material reflectance, $\rho_c$, is known, it can ordinarily be assumed that the surface material reflectance for the aspheric portion is the same. To calculate the reflectivity for the aspheric portion, Equation 33 is evaluated at various points along the $x$-axis.

If the aspheric portion has a different surface material reflectance than the spherical portion, $\rho_a$ will need to be determined using Equation 33 of this chapter and the procedure described in Chapter 9 (specifically using the apparatus depicted in Figure 9). Once $\rho_a$ is known, reflectivity can be calculated at various points on the mirror using Equation 34 of this chapter.

# PART III: STATIC EXPERIMENTS INVOLVING FLAT, CONVEX, AND ASPHERIC MIRRORS

This part of the report presents the results of several static experiments; that is, experiments in which the measurements are taken while test conditions remain unchanged. The objectives of these tests are to characterize mirrors used in the various experiments, to determine needed information that does not appear in the research literature, and also to check information that appears in the literature but may need additional verification.

There are several aspects that must be examined when considering the possible modification of outside rear-view mirrors on light vehicles. Main considerations include:

- Fields-of-view,
- Blind spots,
- Glare,
- Distance estimation,
- Image distortion,
- Driver performance (under realistic conditions), and
- Driver acceptance.

The static experiments deal primarily with the first four of the above, whereas the latter three will be handled later in dynamic tests. Chapter 12 deals with measured characterization of the mirrors used for experimentation, and Chapters 13 through 17 describe the static experiments that were carried out to increase understanding of how the mirrors are used and how drivers react to them.

## CHAPTER 12: MEASUREMENT OF BASIC PARAMETERS FOR MIRRORS USED IN THE STUDY

### Introduction

Prior to undertaking experiments involving the various mirrors that were gathered together for this study, it was deemed desirable to make measurements of the various mirror parameters. Doing so allowed the previously presented analyses and procedures to be checked (Part II of this report), while at the same time determining the actual characteristics of the mirrors, along with their similarities and differences.

Nine mirrors were selected for these tests; four on the driver side and five on the passenger side. These nine mirrors were expected to be used throughout the static experiments, and also throughout the dynamic experiments to follow. All of the mirrors provided an exact fit to the research vehicle to be used, a 2001 Saab 9-5. This vehicle was chosen because it was the type of vehicle that had been sold in a several countries and therefore had a wide variety of factory original replacement mirrors that could be fitted. These mirrors were obtained with the help of General Motors personnel both in Warren, Michigan, and at the Saab Division in Sweden (see Acknowledgements section of this report). Those mirrors that could be purchased here in the United States were ordered from a local Saab dealership, while the others were donated by GM and Saab.

The mirrors were in three classes: planar (or flat), convex (having a spherical surface), and aspheric (having an inner portion that was also a spherical surface, and an outer portion that had a decreasing horizontal radius of curvature, that is, increasing curvature.) The specific purpose of the measurements was to specify the following:

- The actual radius of curvature of each “flat” or convex portion,
- The reflectivity of the flat or convex portion,
- The surface material reflectance (assumed to be uniform over the mirror), and
- Additional parameters associated with the aspheric mirrors.

### Procedure

*Radius of Curvature*

Initially, each mirror was measured to obtain its offset, $h_0$, in the “flat” or spherical portion. These measurements were made using the precision instrument shown in Figure 7 of Chapter 9, and the corresponding procedure described there. Both horizontal and vertical offsets were first obtained. Thereafter, an average offset was computed. The three values were then used to calculate the horizontal, vertical, and average radii of curvature, with results as shown in Table 2. Note that the various actual radii do not differ greatly from the nominal values. All radii are positive, except for the “planar” mirror on the passenger’s side. This mirror was actually slightly concave, but the deviation from flat was considered to be small enough to be unimportant.

**Table 2. Radii of curvature of the mirrors.**

| Vehicle side | Mirror type | VTTI designation | Nominal Radius of Curvature | Actual horizontal Radius of Curvature (mm) | Actual vertical Radius of Curvature (mm) | (H & V Av) Radius of Curvature (mm)* |
|---|---|---|---|---|---|---|
| Driver Side | Planar | F | ∞ | 38313 | 22059 | 27998 |
| | Convex | C20 | 2000 mm | 1926 | 2080 | 2000 |
| | Aspheric | A14 | 1400 mm | 1361 | 1334 | 1347 |
| | Aspheric | A20 | 2000 mm | 1989 | 2068 | 2028 |
| Passenger Side | Planar | F | ∞ | 121325 | -72795 | -363976 |
| | Convex | C14 | 1400 mm | 1400 | 1430 | 1415 |
| | Convex | C20 | 2000 mm | 1978 | 2045 | 2011 |
| | Aspheric | A14 | 1400 mm | 1379 | 1348 | 1364 |
| | Aspheric | A20 | 2000 mm | 1931 | 1968 | 1949 |

* Mirror Horizontal and vertical offsets, $h_o$, were averaged to obtain the calculated average radius of curvature

*Reflectivity and Surface Material Reflectance*

Next, the various mirrors were taken to a darkroom for reflectivity measurements. A point source lamp was used for this procedure, as shown in Figure 9 of Chapter 9 and described in the text. Recall that two factors enter into reflectivity: the surface material reflectance and the curvature. The measurement of reflectivity includes these two factors. For the flat and convex portions of the mirrors, reflectivity is the ratio of $L_F$ or $L_C$ to $L_0$, as described in the text. It gives a realistic indication of how much light is reflected back by the mirror into a driver's eye, as compared with looking at the source from the same total distance. The equations show that reflectivity decreases as the convexity increases. Thus, convexity should reduce glare, but at the cost of making images smaller. In addition, convexity means that more sources of glare are likely to be included because of the greater angle of coverage.

Surface material reflectance is different from reflectivity and deals exclusively with the surface treatment of the mirror, that is, the "silvering." Thus, it does not take into account the effect of mirror curvature. Given the previous parameters as well as the corresponding distance measurements, it is possible to calculate the surface material reflectance (as described in Chapter 9). The calculated values are shown in Table 3. Note that the values in the table account for the actual average radii of curvature, as opposed to the nominal radii of curvature. As can be seen, the values for the various mirrors are quite similar, suggesting that they all had the same or similar surface treatments.

**Table 3. Reflectivity and surface reflectance of the mirrors.**

| Vehicle side | Mirror type | VTTI designation | Nominal Radius of Curvature | $L_o$ (lux) | $L_F$ or $L_C$ (lux) | Reflectivity | Calculated Surface Reflectance, $\rho_F$ or $\rho_C$ |
|---|---|---|---|---|---|---|---|
| Driver Side | Planar | F | ∞ | 34.65 | 17.6 | 0.508 | 0.542 |
| | Convex | C20 | 2000 mm | 34.7 | 9.4 | 0.271 | 0.575 |
| | Aspheric | A14 | 1400 mm | 34.75 | 6.9 | 0.199 | 0.560 |
| | Aspheric | A20 | 2000 mm | 34.8 | 9.8 | 0.282 | 0.593 |
| Passenger Side | Planar | F | ∞ | 34.8 | 18.5 | 0.532 | 0.529 |
| | Convex | C14 | 1400 mm | 34.9 | 7.1 | 0.203 | 0.551 |
| | Convex | C20 | 2000 mm | 34.95 | 9.7 | 0.278 | 0.587 |
| | Aspheric | A14 | 1400 mm | 35 | 7.1 | 0.203 | 0.566 |
| | Aspheric | A20 | 2000 mm | 35.1 | 9.3 | 0.265 | 0.572 |

*Other Dimensional Parameters*

Additional parameters were required to fully define the horizontal equations of the mirrors. These involve determination of projected width of the flat/spherical portion along the horizontal centerline, $d_1$; overall projected horizontal width along the horizontal centerline, $d_2$; total angular change from inside to outside horizontal tangents, $\theta_E$; and cubic-term coefficient, $k$. Note that for the flat and spherical mirrors the overall projected width and the flat/spherical centerline width are the same, because there is no aspheric portion. Therefore, $d_1$ equals $d_2$ for flat and spherical mirrors. These measurements make it possible to define the mirror horizontal center-line equations. The measurements are given in Table 4.

**Table 4. Other dimensional parameters of the mirrors.**

| Vehicle side | Mirror type | VTTI designation | Nominal Radius of Curvature | Flat/Spherical C.L. width $d_1$ (mm) | Overall Projected C.L. width $d_2$ (mm) | Overall Projected C.L. height (mm) | Angular Change, $\theta_E$ (degrees) | Calculated k |
|---|---|---|---|---|---|---|---|---|
| Driver Side | Planar | F | ∞ | 173 | 173 | 99 | - | - |
| | Convex | C20 | 2000 mm | 173 | 173 | 99 | - | - |
| | Aspheric | A14 | 1400 mm | 127 | 173 | 99 | 11 | 1.02251E-05 |
| | Aspheric | A20 | 2000 mm | 114 | 173 | 99 | 13 | 1.39087E-05 |
| Passenger Side | Planar | F | ∞ | 173 | 173 | 99 | - | - |
| | Convex | C14 | 1400 mm | 173 | 173 | 99 | - | - |
| | Convex | C20 | 2000 mm | 173 | 173 | 99 | - | - |
| | Aspheric | A14 | 1400 mm | 125 | 173 | 99 | 11 | 9.61684E-06 |
| | Aspheric | A20 | 2000 mm | 115 | 173 | 99 | 13 | 1.40472E-05 |

*Mirror Equations*

Chapter 11 contains the horizontal centerline equations for spherical and aspheric mirrors. They are repeated here for convenience:

Convex mirrors:

$$y = R_c + \left(R_c^{\,2} - x^2\right)^{1/2} \qquad ; 0 \le x \le d_2 \tag{40}$$

Aspheric mirrors:

$$y = \begin{cases} R_c - \left(R_c^{\,2} - x^2\right)^{1/2} & ; 0 \le x \le d_1 \\ \\ R_c - \left(R_c^{\,2} - x^2\right)^{1/2} + k\left(x - d_1\right)^3 & ; x > d_1 \end{cases} \tag{41}$$

The parameters contained in the equations appear in Tables 2, 3, and 4. Note that the value $R_c$ in the equations should be set equal to the horizontal radius of curvature values given in Table 2.

## CHAPTER 13: OBJECTIVE IN-SITU ANGULAR COVERAGE AND REFLECTIVITY TESTS

### Introduction

The purpose of these static tests was to compare the reflectivity of various rear-view mirrors in a situation very similar to that encountered while driving. Because of the structure of the tests, they also provided information on the relative fields of view of the various mirrors. The tests were performed using an actual automobile (Saab 9-5) with the outside rear-view test mirrors mounted over the usual mirrors. Both driver-side and passenger-side mirrors were examined. The results provided an indication of the reflectivity as a function of angle in practical terms, allowing direct comparisons across the various mirrors.

In this experiment, a single headlamp was used as the source. It was moved in an arc so that it was always equidistant from the outside rear-view mirror at which it was aimed (Figure 15). The headlamp was a large, rectangular halogen lamp (Sylvania #H6054) commonly used on SUVs in the United States The headlamp and its regulated power supply were mounted on a camera tripod to facilitate aiming at the mirror being examined. The high beam of the headlamp was energized during the tests, and it was always set at a height of 32 in (81.3 cm) above the floor. This height was used because it falls near the average headlight height for late-model light vehicles in the United States

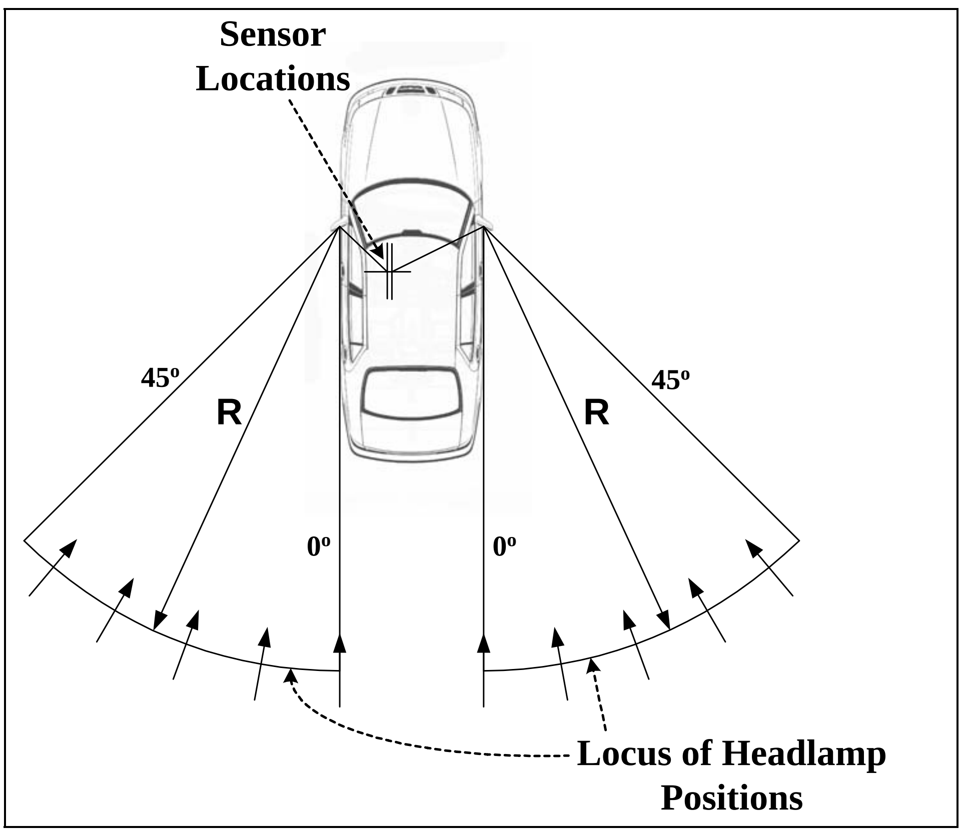


**Figure 15. Diagram depicting the experimental arrangement.**

A digital light meter sensor was placed at the nominal driver's eye position (a point on the bridge of the nose between the two eyes) and was aimed at the mirror being examined. (Note that the nominal position differed slightly for the driver-side and passenger-side mirrors. This is a result of neck swiveling, which causes the eyes to be located at different nominal positions when using the two different mirrors.) The particular meter used, Extech model 403125, was selected because it had an extended sensitivity range.

All tests took place in a darkened storage building. The vehicle side windows (through which the mirrors would ordinarily be viewed) were in the raised position, as in normal driving. These side windows had a slight tint. The floor of the building was surveyed with landmarks drawn with chalk. In all cases, the headlamp was placed so that it was 20 ft (6.1 m) from the center of the mirror for which measurements were being made (Figure 15). The arc of headlamp positions began at a point that was straight back from the mirror; that is, along a line passing through the mirror, parallel to the longitudinal axis of the vehicle. The arc continued around to the side to the 45 deg position (the point at which none of the mirrors produced a reflection). Thus, measurements could be made from 0 deg (straight back) to 45 deg, corresponding to a diagonally rearward position.

### Procedure

The specific mirror to be measured was placed over the existing mirror using hook and loop adhesive backed tape (commonly referred to as Velcro). Figure 16 shows how the mirrors were attached. All protrusions from the back of the test mirrors had been machined away, so that the mirrors would lay flat against the factory-installed underlying vehicle mirror (which had strips of loop attached to it).

**Figure 16. Method of attachment for the outside rear-view mirrors.**

Once a mirror was installed, it was aimed from the nominal driver's eye position so that the headlamp placed in the 0 deg position was just fully visible at the inner edge of the mirror. This corresponded closely to having the inside edge of view tangent to the side of the vehicle. In terms of vertical aiming, the mirror was adjusted so that the headlamp appeared along the horizontal centerline (vertical center) of the mirror. After mirror adjustment, the sensor was mounted on a second tripod which placed it at the nominal driver's eye position.

To take the measurements for a given mirror, Experimenter 1 worked inside the vehicle, while Experimenter 2 worked outside the vehicle by moving and adjusting the headlamp tripod. Experimenter 1 first aimed the sensor at the mirror. Then Experimenter 2 aimed the headlamp in azimuth and elevation while Experimenter 1 read values. The objective was to maximize the reading by aiming the headlamp. This maximum value was recorded. Data gathering then continued by moving the headlamp tripod to the next position, or until all data had been gathered for the given mirror.

In total, nine mirrors were tested in the experiment: four on the driver side and five on the passenger side. The mirrors are the ones specified in Tables 2, 3, and 4 of Chapter 12.

As can be seen, each mirror tested on the driver side had a corresponding mirror that was tested on the passenger side. In addition, a 1,400 mm radius-of-curvature convex mirror was tested on the passenger side. This mirror corresponds to the convex mirror ordinarily found on the passenger side of U.S. light vehicles except that it did not have a legend imprinted on it.

It should be noted that results on the driver side would be expected to differ from results on the passenger side, for a given matching pair of mirrors. The reason for this is that the nominal eye to mirror distances differ. Note specifically that for convex and aspheric mirrors, the light is spread over a greater region as the mirror is moved away from the eye. Consequently, if all other aspects are the same, a mirror mounted on the passenger side should produce slightly lower readings than the corresponding mirror mounted on the driver side (as described earlier in Chapters 7 and 8). Thus, it was necessary to perform tests on both sides of the vehicle.

## Analysis and Results

### *Main Results*

The main results of the experiment are most easily explained in terms of the graph showing the reflected illuminance results (Figure 17). This graph plots the reflected illuminances for the driver side and passenger side mirrors as a function of the source angle. This angle is always measured from a line that passes through the center of the mirror and is parallel to the longitudinal axis of the vehicle, as previously explained.

The graph shows very clearly that the two flat mirrors (F) produced the highest reflected illuminance by a wide margin, but did so over a relatively narrow field-of-view. In the case of the driver side mirror, the field-of-view was approximately 12 deg, while for the passenger side the field-of-view was about 7.5 deg. There is a very sharp drop-off in reflected illuminance for these mirrors. This corresponds to the reflection moving out of the field-of-view of the mirror.

The convex mirrors with radii of curvature of 2,000 mm (designated as C20) produced much lower levels of peak illuminance, but produced reflected illuminance over greater angles, as expected. On the driver side the field extends to 21 deg, whereas on the passenger side it extends to about 16.5 deg. The cutoffs are again quite sharp, as the light source moves out of the field-of-view.

The aspheric mirrors with spherical portions having radii of curvature of 2,000 mm (designated as A20) had reflected illuminances similar to those of the C20 mirrors for smaller angles. However, the reflected illuminances dropped off at smaller angles, but then continued out to very large angles, namely 40 deg on the driver side and 37 deg on the passenger side. These gradual tapering effects are a result of the aspheric portions, which pick up some reflected light over relatively large angles.

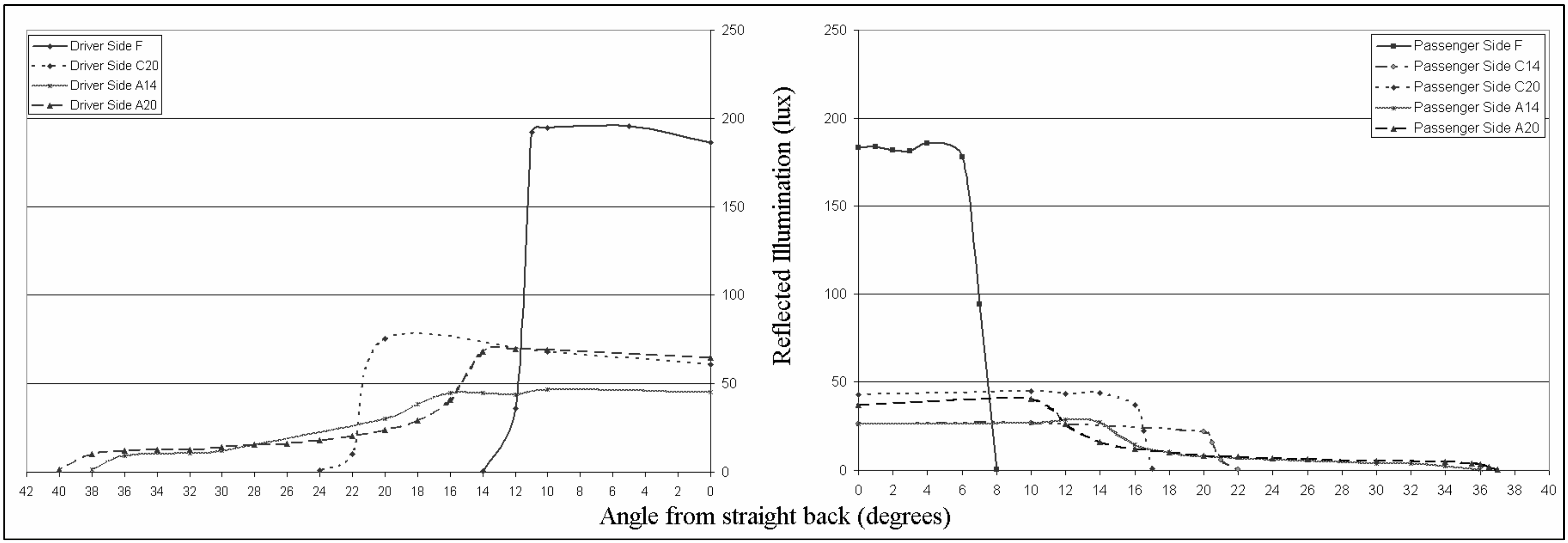


**Figure 17. Reflected illumination at the driver's eye position for outside rear-view mirrors.**

The convex mirror on the passenger side with radius of curvature of 1,400 mm (designated as C14) had even lower reflected illuminance than that of C20, but had a field of reflection that extended out to about 20.5 deg. The aspherics with spherical portions having radii of curvature of 1,400 mm (designated as A14) had the same level of reflected illuminance as the C14 mirror for small angles, but tailed off much more slowly, as expected. The aspheric portion causes this gradual roll-off, producing some reflected illuminance out to 38 deg on the driver side and 35 deg on the passenger side.

### *Additional Results*

The previous results were obtained with the side windows in the up position. It was believed that such a configuration would produce the most realistic results in terms of reflected illumination. Drivers generally drive with their windows up, particularly at night when glare becomes a problem. However, to obtain an idea of the effect of the windows, reflectivity measurements were made at one position with the side window both up and down. This provided an indication of the approximate effect of the window. For the zero degree passenger-side position, the illuminance using the flat mirror (F) was found to be 255 lux with the window down. The corresponding window-up value was 182 lux. Thus the window transmissivity, which is given by the ratio of the two values, was approximately 0.71. Note however that the light entering the sensor (corresponding to the driver's eye position) would pass through the glass at an angle of perhaps 15 deg to the perpendicular of the glass (75 deg from tangent to the glass). Thus, while transmissivity is a function of angle of incidence, it does not change appreciably in actual mirror use.

## Conclusions

In general, the plots provide highly instructive information on the trade-offs that exist among the various mirrors, in terms of reflected illumination and corresponding angular coverage. The following statements can be made:

- The plots of Figure 17 provide very clear indications of the angular coverage afforded by each type of mirror. As the external headlamp passes out of the field-of-view, there is a relatively sharp drop in reflected illumination. Consequently, the plots allow comparison of the one-eyed angles of view that each mirror provides.
- For aspheric mirrors, it is possible to discern the angular coverage of the spherical part of the mirror as well as the extended coverage provided by the aspheric portion of the mirror. Note in Figure 17 that the delineator between these two portions is at the point where reflected illuminance attenuates to a lower value.
- Flat mirrors create the highest reflected illuminance by a wide margin, but do so over relatively narrow fields-of-view. However, the fields-of-view are those that would be most closely associated with a vehicle moving up from the rear in either the adjacent right lane or adjacent left lane. Flat mirrors have a sharp cutoff, which occurs when the illumination source moves out of the field of reflection.

# CHAPTER 14: EVALUATION OF BLIND AREAS FOR VARIOUS DRIVER-SIDE REAR-VIEW MIRRORS

## Introduction

It is generally accepted that the main advantage of using convex and aspheric mirrors in place of flat mirrors is to increase the field-of-view that results. Accordingly, blind spots along the side of the vehicle are reduced in size. However, the analyses done in regard to blind spots are limited, making it difficult to assess the specific size of the blind areas as a function of mirror type. Platzer (1995) provided an analytic approach, but did not show any comparisons across mirror types. Flannagan, Sivak, and Traube (1999) depicted the blind area as the area between the outer edge of the field-of-view of the mirror and the peripheral view for direct looks (Figure 3, Chapter 2). However, the 180 deg field assumed for direct looks may have been optimistic.

In examining how to assess blind areas, the current research team found that the B-pillars often limit the direct-look field-of-view to the side and rear. This is particularly true for four-door cars because the doors are usually somewhat narrower than for two-door cars. The B-pillars are then farther forward, resulting in limited side viewing. Two-door cars often have no pillar between the front-side glass and the rear-side glass, and the doors are usually wider. Thus, two-door cars may not have traditional B-pillars or have them so far back as to not obstruct side vision. In such cases, driver peripheral vision limitations determine how large the view is along the side of the vehicle. The B-pillar problem is *not* covered in any known previous reference.

Earlier, a static experiment was performed showing the fields of reflectivity for various mirrors as obtained at the driver's seat (Figure 17, Chapter 13). That experiment provided relative fields of view for nine different mirrors. The C14 mirror on the driver's side was not included because it was not available at that time. However, based on the ratio of passenger-side fields of view, it is possible to accurately estimate the response that such a mirror would provide, as shown in Figure 18. The figure then shows the relative coverage for the various mirrors. Table 5 presents the values extracted from the figure.

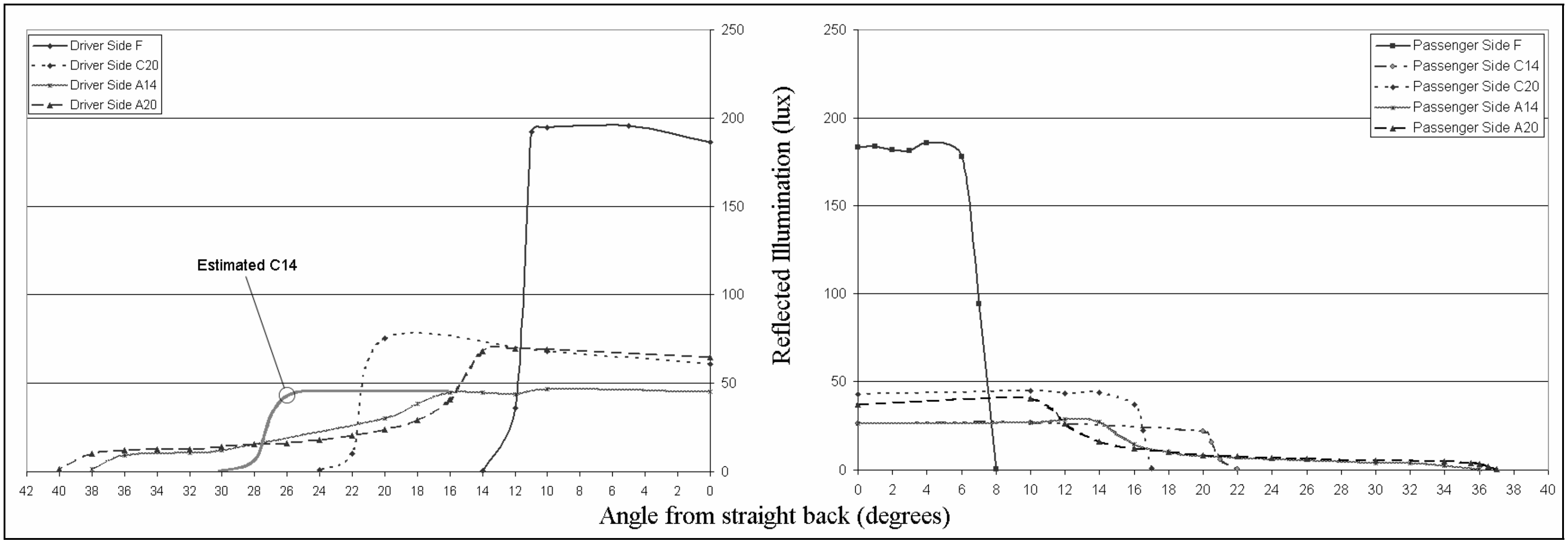


**Figure 18. Reflected illumination at the driver's eye position for outside rear-view mirrors, with the C14-D response estimated.**

**Table 5. Angular coverage of five driver-side mirrors, extracted from Figure 18.**

| Mirror | Flat | C20 | C14 | A20 Convex Portion | A20 Overall | A14 Convex Portion | A14 Overall |
|---|---|---|---|---|---|---|---|
| Coverage in Deg | 12.0 | 21.5 | 27.0 | 15.0 | 39.0 | 18.0 | 37.0 |

**Experiment**

The starting point for assessing blind areas was to conduct an experiment in which driver-side fields of view were measured for ordinary drivers in *their own* cars. In this experiment, drivers were not permitted to adjust their mirrors or their seat positions. Instead, it was assumed that the mirrors and seat positions were already set according to their usual driving preferences. Since all mirrors were flat, data for mirror field-of-view could only be obtained for flat mirrors.

Twenty-five drivers, all of whom were employees of Virginia Tech Transportation Institute, were asked to sit in their own parked vehicles with the driver-side window down (the experiment was limited to those who drove automobiles). They were requested to point their heads toward the driver-side A-pillar, a position that closely corresponds to head angle when looking into the outside rear-view mirror. It is known that drivers do not swivel their heads all the way to the direction of the mirror. Instead, they swivel their heads roughly to the A-pillar direction and then use additional eye direction change to look into the mirror. All measurements were made with the driver looking into the mirror and head directed toward the A-pillar.

One experimenter positioned himself along the side of the vehicle and to the rear. He held a brightly colored vertical stick. He moved forward until the stick could no longer be seen by the driver. Once the edge of the field was established through a fine adjustment, a second experimenter measured the angle from the rear longitudinal axis of the vehicle to the edge of the field-of-view. This experimenter first established the tangent to the longitudinal axis and placed one leg of a large protractor along the tangent. The experimenter then opened the protractor until the second leg pointed at the stick.

Next, the experimenters established the direct look field limit angle. The driver was instructed to maintain the original head position and to look into the mirror. If the driver could see the B-pillar in his or her peripheral vision (not related to mirror coverage), then measurements were made using the angle to the B-pillar. If the B-pillar could not be seen, then the driver's peripheral field limit was used. Peripheral field limit, when required, was obtained by having the experimenter move forward with the colored stick along the side of the vehicle until the driver could detect it.

After fine adjustments, measurements were made by the other experimenter by measuring the angle from the lateral axis to the B-pillar or peripheral vision limit, whichever was applicable. The pivot point of the protractor was placed at the bridge of the nose of the driver. Later, the (90 deg) complement of the measured angle was obtained so that the vision limit relative to the rear longitudinal axis was obtained.

It is important to note that the direct look angle obtained in this experiment corresponds to the driver using peripheral vision only, and not turning the head as far as possible. This corresponds to the case in which it is believed that most incidents occur. Clearly, if the driver did carefully look to the outside rear directly, there would be no incident (although he or she might become involved in a conflict with a vehicle directly ahead). Thus, it is believed that the measurements taken are reasonably representative of actual fields of view with flat mirrors for the case in which a side-related incident might occur.

### Results

Table 6 shows the results of the experiment for the 25 drivers. The column labeled "F.O.V. max angle" shows the coverage provided by the flat mirror. As shown, the mean value was 12.6 deg. The limit of direct vision is shown in the column labeled "Complement of B-pillar Angle." This angle had a mean value of 58.8 deg. Note that this angle is substantially greater than that estimated by Flannagan et al. (1999), i.e., 45 deg, which implies that the coverage by direct vision is somewhat smaller than they had suggested (corresponding to a larger blind area).

**Table 6. Field-of-view (with flat mirror) and direct view limit for 25 drivers in their own cars.**

| Subject # | M/F | Height (in) | Vehicle Description | Angle to B-Pillar | Complement of B-pillar Angle | F.O.V. max angle |
|---|---|---|---|---|---|---|
| 1 | F | 66 | 2 Door (with B) | 48 * | 42 * | 10 |
| 2 | F | 68 | 4 Door (Hatch) | 17 | 73 | 10 |
| 3 | F | 64 | 4 Door (Sedan) | 20 | 70 | 11 |
| 4 | F | 65 | 4 Door (Sedan) | 29 | 61 | 14 |
| 5 | M | 71 | 2 Door (No B) | 40 * | 50 * | 13 |
| 6 | M | 72 | 2 Door (with B) | 45 | 45 | 16 |
| 7 | F | 66 | 4 Door (Hatch) | 41 | 49 | 13 |
| 8 | M | 71 | 4 Door (Sedan) | 9 | 81 | 13 |
| 9 | M | 70 | 2 Door (with B) | 32 | 58 | 10 |
| 10 | F | 64 | 4 Door (Sedan) | 29 | 61 | 14 |
| 11 | F | 59 | 4 Door (Sedan) | 40 | 50 | 18 |
| 12 | M | 76 | 2 Door (with B) | 43 * | 47 * | 7 |
| 13 | F | 68 | 4 Door (Sedan) | 38 | 52 | 13 |
| 14 | M | 70 | 4 Door (Sedan) | 25 | 65 | 13 |
| 15 | F | 64 | 2 Door (No B) | 28 * | 62 * | 13 |
| 16 | F | 66 | 4 Door (Sedan) | 22 | 68 | 12 |
| 17 | M | 74 | 2 Door (with B) | 48 * | 42 * | 14 |
| 18 | F | 65 | 2 Door (with B) | 39 * | 51 * | 12 |
| 19 | F | 70 | 4 Door (Sedan) | 9 | 81 | 10 |
| 20 | F | 64 | 4 Door (Sedan) | 39 | 51 | 15 |
| 21 | M | 69 | 4 Door (Sedan) | 25 | 65 | 16 |
| 22 | M | 69 | 4 Door (Sedan) | 14 | 76 | 10 |
| 23 | M | 72 | 4 Door (Sedan) | 27 | 63 | 10 |
| 24 | M | 70 | 2 Door (with B) | 49 * | 41 * | 17 |
| 25 | M | 73 | 4 Door (Sedan) | 24 | 66 | 12 |
| **Average** | | **68.24** | | **31.20** | **58.80** | **12.64** |
| **Standard Dev** | | **3.91** | | **12.06** | **12.06** | **2.58** |

* *Unobstructed peripheral vision limit*

The 12.6 degree mean mirror field-of-view obtained in this experiment is quite close to the 12.0 degree field-of-view obtained in the earlier reflected illumination experiment (Table 5). This suggests that reflected illumination values are likely to be representative of fields of view for the convex and aspheric mirrors. To calculate the fields of view for the four non-flat mirrors, the values in Table 5 were multiplied by 12.6 and then divided by 12.0. In other words, the small correction factor occurring for the flat mirror was applied to the other mirrors, on the assumption that mirror positions would be similar. This assumption is necessary because there are no data available on how drivers would adjust non-flat driver-side mirrors in everyday use, if the mirrors were prevalent in the United States.

Mean angular data for the experiment are summarized in Table 7. The first row of data show the actual (flat mirror) and projected (all other mirrors) angles of coverage associated with the various mirrors. As indicated, these are angles measured from the rear longitudinal axis. The second row shows the direct look angles measured in the same way. The angles are all the same, since they are not expected to change with the type of mirror. Finally, the third row shows the blind angles, which are obtained by subtracting the mirror coverage angle from the direct view limit. The blind angle corresponds to the blind area. Thus, the smaller the blind angle, the smaller is the blind area. Clearly, the flat mirror has the largest blind area, the convex mirrors have somewhat smaller blind areas, and the aspheric mirrors have the smallest blind areas. These results are as expected, based on the reflected illumination diagram of Figure 18.

**Table 7. Angular coverage, direct view limit, and blind angle as a function of mirror type.**

| | Average Actual | Projected | | | | | |
|---|---|---|---|---|---|---|---|
| Mirror Type | Flat | C20 | C14 | A20 Convex Part | A20 Overall | A14 Convex Part | A14 Overall |
| Coverage in Deg * | 12.6 | 22.6 | 28.4 | 15.8 | 41.1 | 19.0 | 39.0 |
| Direct View Limit * in Deg | 58.8 | 58.8 | 58.8 | | 58.8 | | 58.8 |
| Blind Angle in Deg | 46.2 | 36.2 | 30.4 | | 17.7 | | 19.8 |

** Measured from rear longitudinal axis*

Diagrams were drawn to show the blind areas for each of the five mirrors (Figures 19 through 23). Figure 19 shows the actual blind area for the flat mirror. This blind area is quite large and illustrates very clearly the problem that exists with the current U.S. standard, which requires a flat mirror on the driver side for new vehicles. The blind area is sufficient to hide a medium size sedan. Under worst case conditions, which would involve having another vehicle approach along the left edge of the left lane, there is an expanse of approximately 40 ft (12.2 m) during which the approaching vehicle probably could not be seen.  In addition, there could be merges into the left lane from a left side ramp or a third lane that would be completely hidden to the driver in the right lane.

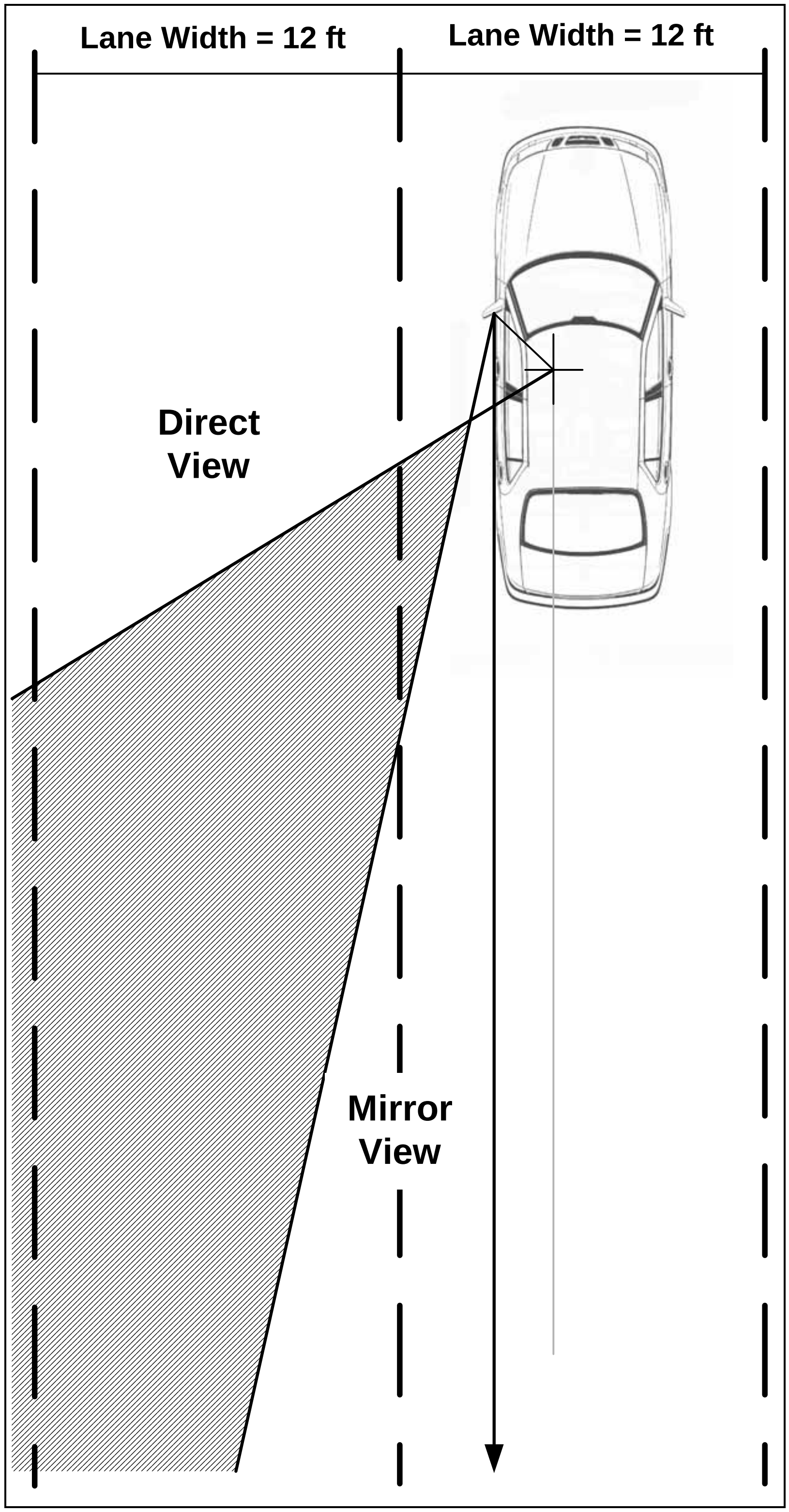


**Figure 19.  Average blind area for the flat mirror, driver side.**

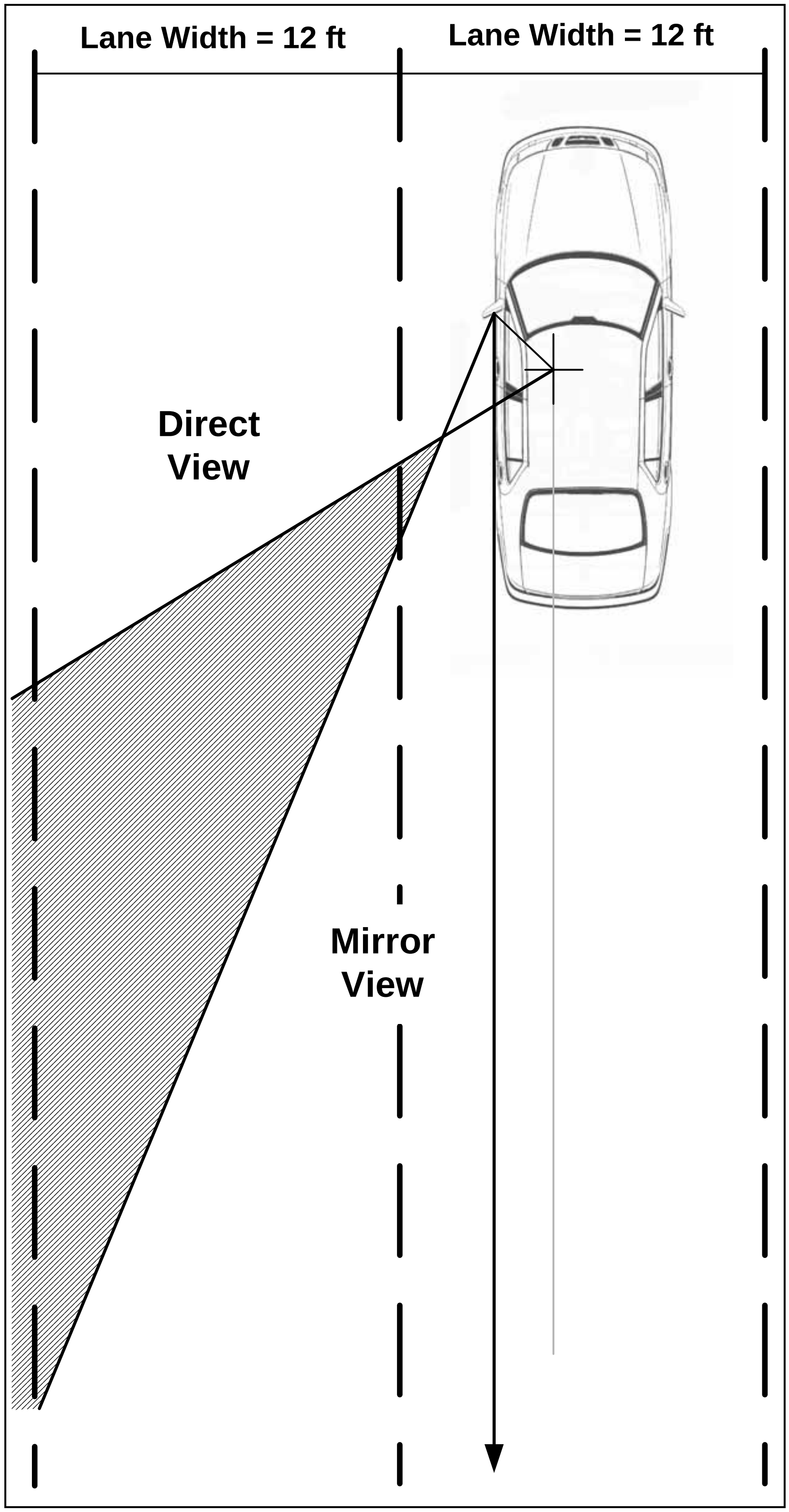


**Figure 20. Projected blind area for a C20 mirror, driver side.**

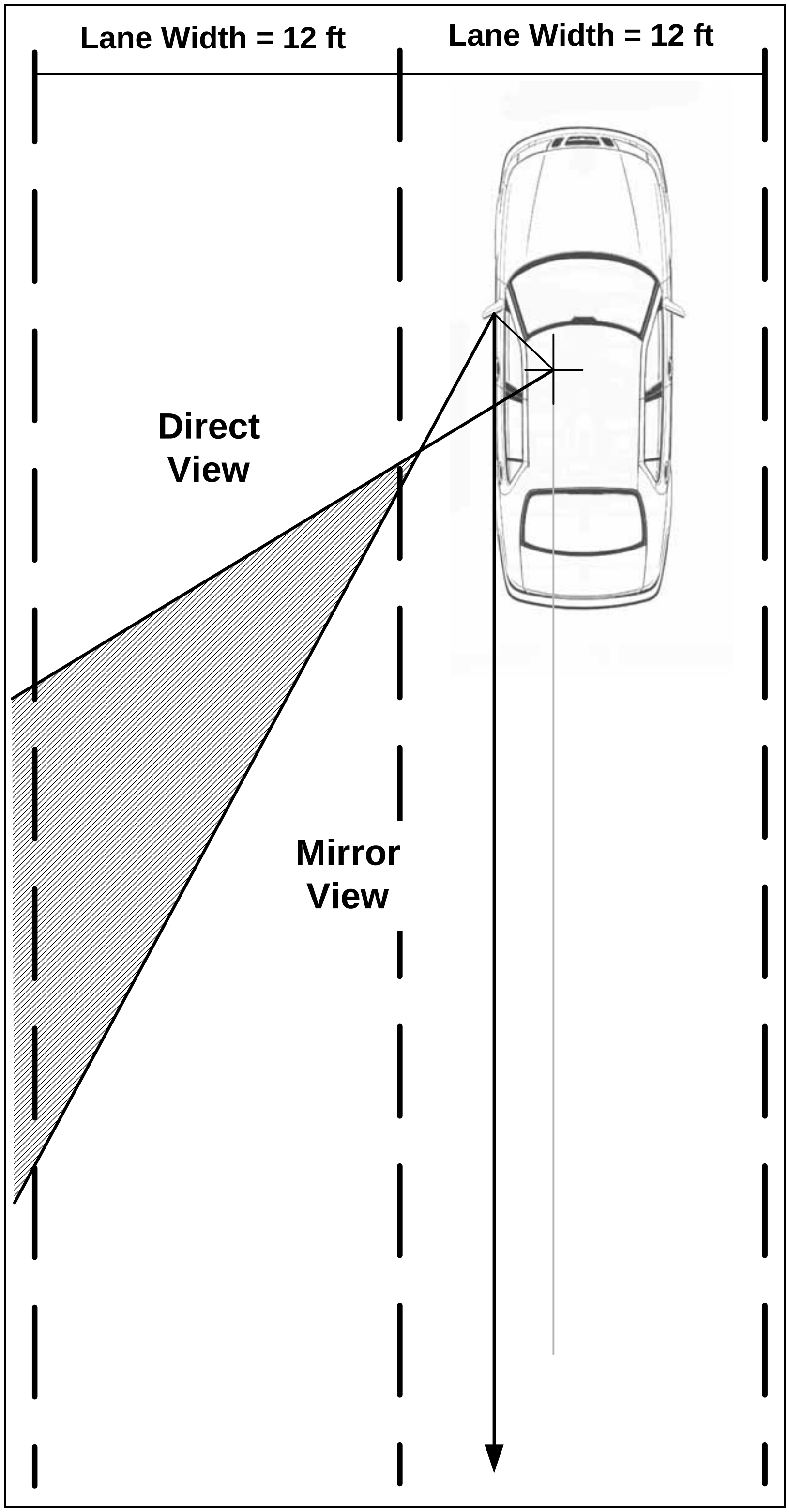


**Figure 21. Projected blind area for a C14 mirror, driver side.**

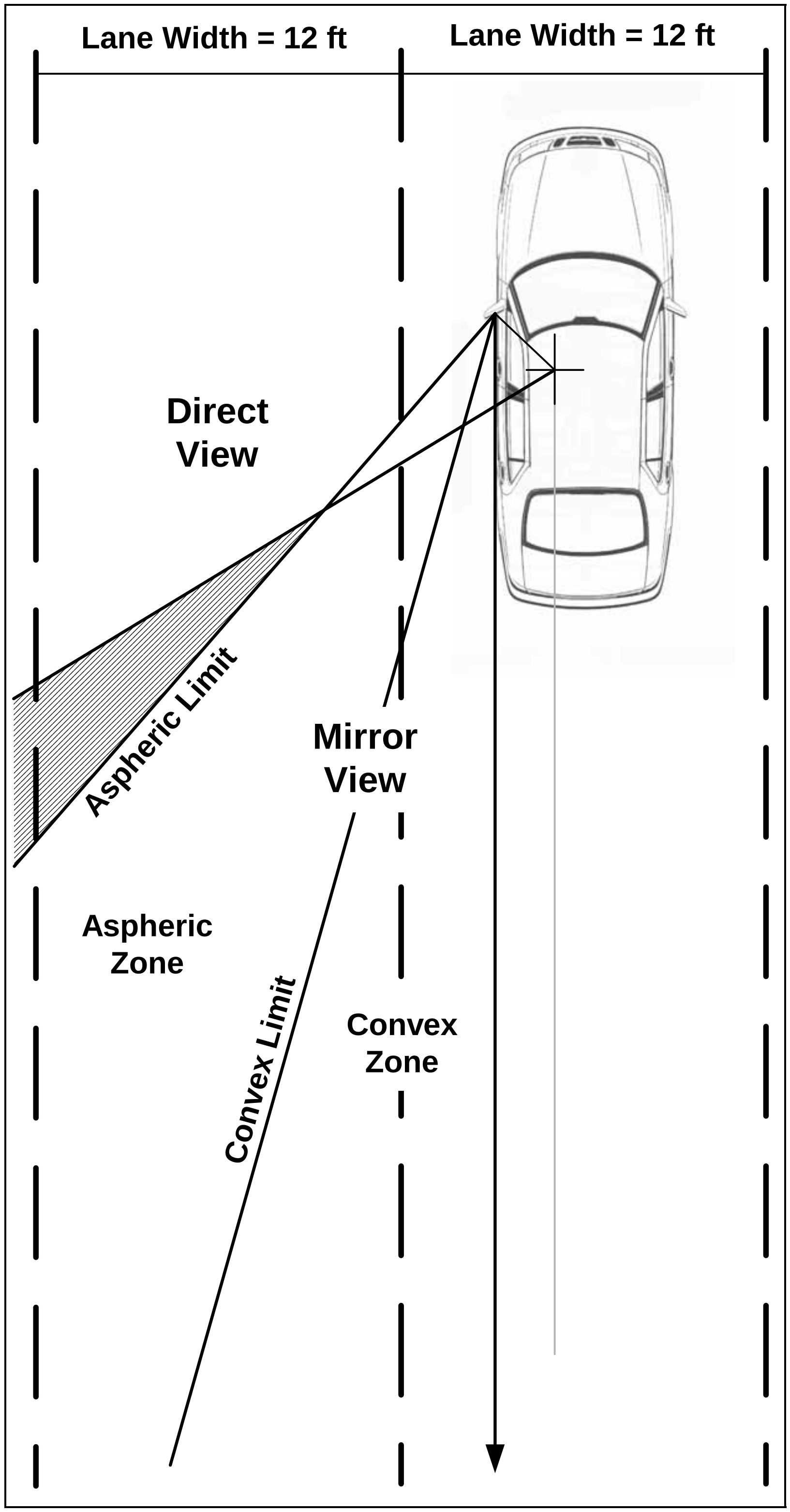


**Figure 22. Projected blind area for an A20 mirror, driver side.**

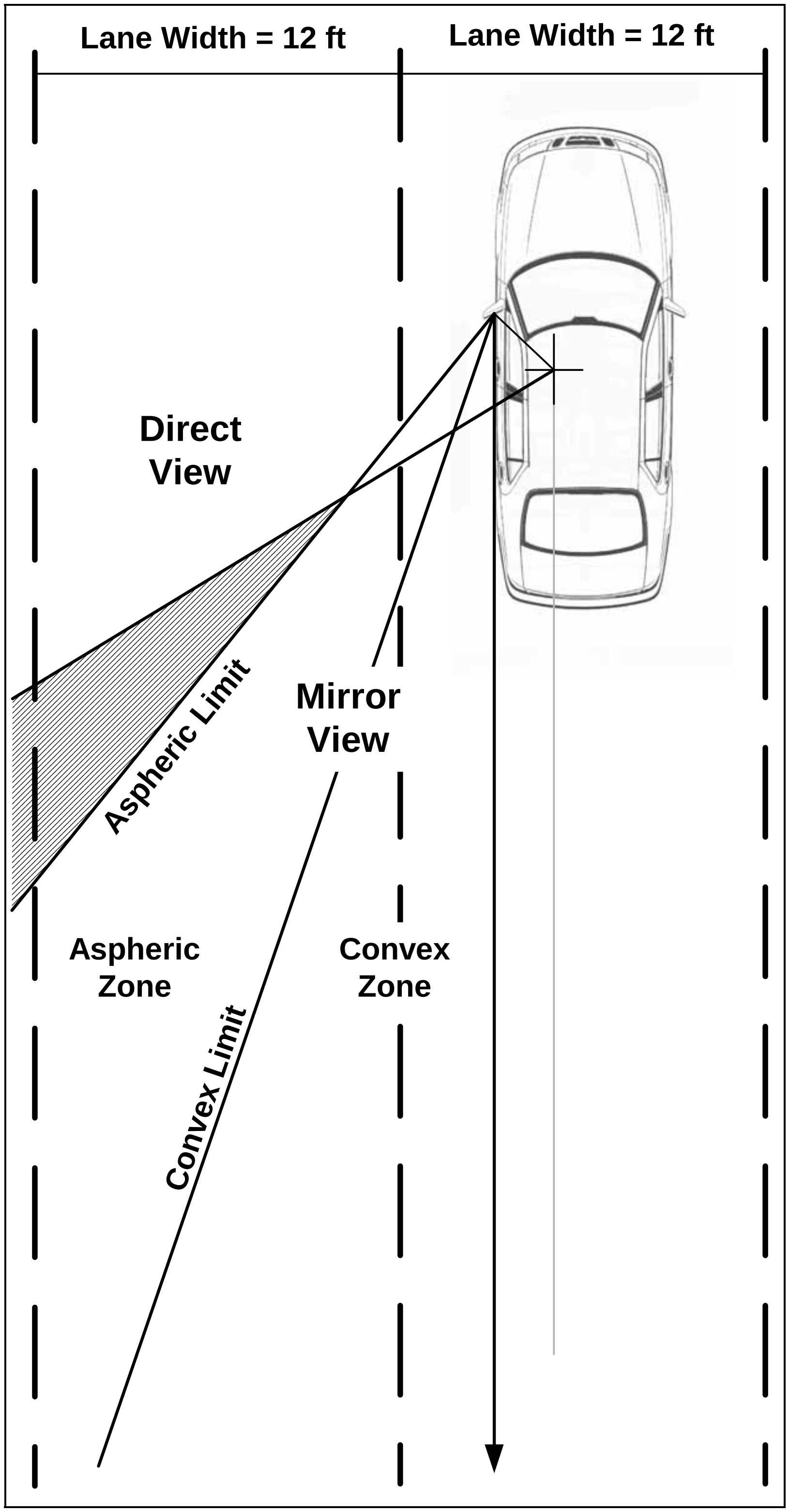


**Figure 23. Projected blind area for an A14 mirror, driver side.**

The remaining figures show that the blind area decreases in the order C20, C14, A14, A20. However, the A14 and A20 blind areas are quite similar. All four of these mirrors provide blind spot reductions that would make it impossible to completely hide a medium-sized sedan. However, in the case of C20, the blind area is still large, suggesting that the possibility of a missed detection might still exist.

The aspheric zones for the aspheric mirrors cover a large percentage of the blind areas that exist for the other mirrors. Consequently, drivers would see distorted images in these regions. However, distorted images are certainly better than *no* images. The aspherics have blind areas that are sufficiently small such that it is highly unlikely a vehicle would go undetected by a driver in the right lane, assuming the driver glances into the outside mirror.

All four of the alternative mirrors would of course produce minified images. This appears to be the price that must be paid for increasing the field-of-view. Current practice on light vehicles is to use a relatively large mirror area, which should contribute to safety by increasing the field-of-view slightly. However, there is a practical limit to mirror size. If mirrors were to be made much larger, they would begin to present a hazard to pedestrians, and in situations where vehicles pass one another or an obstruction with little clearance. In addition, they would begin to affect fuel mileage.

The analyses performed in the current study make use of mean values. Results for individual situations could be expected to vary substantially about these mean values. Blind areas could therefore be expected to vary with the driver, the vehicle, the type of mirror, and the setting of the mirror and the driver's seat. Nevertheless, it is quite clear that the general effect of mirror type is as shown in Figures 19 through 23. In other words, for any given driver, the trends shown in the figures should be the same.

It should be mentioned that there is a possibility of peripheral vision into the left lane from *behind* the B-pillar. This situation might occur more often with taller drivers because their eye positions would be farther back compared with their B-pillars. The analyses reported in this chapter do not take this potential viewing condition into account. In any case, such detection could be considered unreliable, and in addition a large blind spot would still be created by the B-pillar.

### Conclusions

The main conclusion to be drawn from this experiment and analysis is that the flat mirror on the driver side of the vehicle generally creates a large blind area. This area is of sufficient size to hide a normal size sedan over a range of approximately 40 ft (12.2 m). Another important conclusion is that convex and aspheric mirrors are capable of substantially reducing the blind area, but with image minification and with additional distortion in the case of aspherics. Thus, tradeoffs exist, as expected.

## Additional Analyses Involving Driver Height

As mentioned, tall drivers tend to set their seats farther back in the vehicle so that they have adequate room in the driver workspace. This procedure is believed to have three deleterious effects: first, it causes the driver to be farther away from the outside rear-view mirror, creating a smaller field-of-view; second, it may cause the B-pillar to have a greater effect in limiting the direct field-of-view in the adjacent lane because the B-pillar is farther forward relative to the driver's eyes; and third, it may cause the blind area angle to increase.

Statistical tests were performed on the data to determine if these statements were borne out in the data. Initially, the data for the 25 subjects shown in Table 6 were subjected to simple regression analyses. Three such analyses were carried out: one for mirror field-of-view limit as a function of height, one for direct view limit as a function of height, and one for blind area as a function of height. None of these analyses resulted in a significant slope to the corresponding regression line; however, in the case of the mirror field-of-view limit, the result was $t(1,23) = -1.92$; $p = 0.068$.

Next, the data for four-door vehicles only were analyzed (16 drivers). Performing the same analyses, all slope results became significant, as follows:

Mirror field-of-view limit vs. height: $t(1,14) = -2.76$; $p = 0.0154$
slope = -0.378 degree per height inch

Direct view limit vs. height: $t(1,14) = -2.42$; $p = 0.0297$
slope = -1.542 deg per height inch

Blind area angle vs. height: $t(1,14) = 2.71$; $p = 0.0170$
slope = +1.920 deg per height inch

These results demonstrate that, for four-door automobiles, increasing driver height results in significantly smaller coverage angles for the outside rear-view mirror, smaller direct view coverage of the left lane, and greater blind spot area in the left lane. Thus, in four-door automobiles, taller drivers are at a disadvantage in regard to views of the adjacent lane as compared with shorter drivers.

## CHAPTER 15: EVALUATION OF BLIND AREAS FOR PASSENGER-SIDE REAR-VIEW MIRRORS

### Introduction

The previous chapter dealt with evaluation of blind areas created by using various mirrors on the driver side of the vehicle. This chapter deals with the related problem of evaluating the blind areas on the passenger side. The problem of passenger-side evaluation is related, but not the same. Previous chapters have shown that a given mirror does not produce the same results when transferred from one side of the vehicle to the other. Reasons for this have already been explained.

The procedure for evaluating the blind areas on the passenger side similarly have to be modified somewhat to obtain the best results. This occurs because experimental data on how drivers are currently using their mirrors can only be obtained for convex mirrors; that is, the type of mirrors in current use on vehicles. The B-pillar problem also has to be handled differently because drivers generally can see behind the pillar with their peripheral vision on the passenger side. Yet another factor of difference is the head-turn point in using the passenger-side outside rear view mirror.

In terms of similarity, the experimenters again made use of data gathered for group of drivers in their own vehicles, with mirrors in positions previously set by the drivers. These data were supplemented for purposes of extrapolation by the earlier static data showing fields of reflectivity for various candidate passenger-side mirrors (see Figure 18 of Chapter 14). The right-hand graph of that figure contains the passenger-side data. Table 8 of the current chapter shows the angular coverage for four of the five mirrors: two convex mirrors (C20-P, C14-P) and two aspheric mirrors (A20-P and A14-P). The flat mirror data are not included in the table because flat mirrors are not currently used on the passenger side. Also, there are no plans by manufacturers to use flat mirrors because of their extremely narrow field-of-view when used on the passenger side.

**Table 8. Angular coverage of four passenger-side mirrors, extracted from Figure 18 of Chapter 14.**

| Mirror | C20 | C14 | A20 Convex Portion | A20 Overall | A14 Convex Portion | A14 Overall |
|---|---|---|---|---|---|---|
| Coverage in deg | 16.5 | 21 | 12 | 36 | 15 | 34 |

### Experiment

Again, the starting point for assessing blind areas was to conduct an experiment in which fields of view were measured for ordinary drivers in *their own* cars. Drivers were not permitted to adjust their mirrors or their seat positions. Instead, it was assumed that the mirrors and seat positions were already set according to their usual driving preferences.

Since all mirrors were convex, data for mirror field-of-view could only be obtained for convex mirrors. Measurements were made of the radii of curvature for later analysis. In addition, the type of vehicle in terms of window arrangement was noted for later use.

Twenty-five drivers, all of whom were employees of VTTI, sat in their own parked vehicles with the passenger-side window(s) down (the experiment was limited to those who drove automobiles). They were requested to point their heads at a point on the windshield that was three-fourths of the way across the windshield toward the driver-side A-pillar, a position that closely corresponds to head angle when looking into the outside rear-view mirror. This spot was determined prior to data taking for each subject and was designated by a small sticker placed on the inside of the windshield. As indicated previously, it is known that drivers do not swivel their heads all the way to the direction of the mirror. Instead, they swivel their heads partway and then use additional eye direction change to look into the mirror. It had been determined ahead of time that the ¾ point on the windshield was the appropriate head turn direction, believed to be typical of the driving public.

One experimenter positioned himself along the passenger side of the vehicle and to the rear. He held a brightly colored vertical stick. He moved forward until the stick could no longer be seen by the driver. Once the edge of the field was established through a fine adjustment, a second experimenter measured the angle from the rear longitudinal axis of the vehicle to the edge of the field-of-view. This experimenter first established the tangent to the longitudinal axis and placed one leg of a large protractor along the tangent. The experimenter then opened the protractor until the second leg pointed at the stick. The pivot of the protractor was placed directly above the mirror during this process, thereby establishing the outside edge of the field-of-view of the mirror.

Next, the experimenters established the direct look field limit angle. The driver was instructed to maintain the original head position and to look into the mirror. If the driver could see the B-pillar in his or her peripheral vision (not related to mirror coverage), then measurements were made using the angle to the front and rear edges of the B-pillar. If the B-pillar could not be seen, the driver's peripheral field limit or other obstruction limit was used, whichever was smaller. Peripheral field limit, when required, was obtained by having the experimenter move forward with the colored stick along the side of the vehicle until the driver could detect it.

After fine adjustments, measurements were made by the other experimenter by measuring the angle from the lateral axis to the B-pillar or peripheral vision limit, whichever was applicable. The pivot point of the protractor was placed at the bridge of the nose of the driver. Later, the (90 deg) complement of the measured angle was obtained so that the vision limit relative to the rear longitudinal axis was obtained.

It is important to note, once again, that the direct look angle obtained in this experiment corresponds to the driver using peripheral vision only, and not turning the head as far as possible. This corresponds to the case in which it is believed that most incidents occur. Clearly, if the driver did carefully look to the outside rear directly, there would be no incident (although, as mentioned previously, he or she might become involved in a conflict with a vehicle directly ahead). Thus, it is believed that the measurements taken are reasonably representative of actual fields of view for the case in which a side-related incident might occur.

### Results

The experiment results are summarized in Table 9. The participant's car was classified in terms of description (column 4) and type (column 5). Car types are illustrated in Figure 24. Out of the 25 vehicles, only one vehicle did not have a B-pillar (type 1), and there were no type 3 or type 6 vehicles.

**Table 9. Field-of-view (with original equipment passenger-side convex mirror) and direct view limits for 25 drivers in their own cars.**

| Subject # | M/F | Height (in) | Vehicle Description | Type of Car | Radius of Curvature (mm) | Mirror F.O.V. max angle | Peripheral/Pillar limit angle complement | B-Pillar limit to rear complement | B-Pillar limit to front complement |
|---|---|---|---|---|---|---|---|---|---|
| 1 | M | 69 | 4-door st wag | 5 | 1,055.44 | 23 | 44 | 74 | 82 |
| 2 | M | 71 | 4-door sedan | 4 | 1,450.42 | 21 | 57 | 74 | 83 |
| 3 | F | 64 | 2-door no B | 1 | 1,358.46 | 17 | 69 | - * | - * |
| 4 | F | 62 | 4-door sedan | 4 | 1,003.15 | 16 | 54 | 74 | 80 |
| 5 | F | 70 | 4-door sedan | 4 | 1,028.63 | 25 | 44 | 73 | 82 |
| 6 | F | 66 | 4-door sedan | 5 | 1,014.32 | 27 | 48 | 72 | 77 |
| 7 | F | 68 | 4-door hatch | 5 | 1,300.27 | 20 | - (67)** | 74 | 80 |
| 8 | M | 70 | 4-door sedan | 4 | 1,498.15 | 20 | 47 | 72 | 79 |
| 9 | F | 64 | 4-door sedan | 5 | 1,319.11 | 22 | 41 | 70 | 74 |
| 10 | M | 72 | 2-door with B | 2 | 1300.27 | 29 | 46 | 69 | 80 |
| 11 | M | 72 | 4-door sedan | 4 | 1,400.24 | 15 | 48 | 74 | 81 |
| 12 | F | 65 | 2-door with B | 2 | 1,343.43 | 22 | 47 | 71 | 76 |
| 13 | M | 68 | 2-door with B | 2 | 1,479.89 | 25 | 44 | 69 | 75 |
| 14 | M | 70 | 4-door sedan | 4 | 1,011.50 | 22 | 54 | 76 | 83 |
| 15 | M | 74 | 4-door sedan | 5 | 1,061.59 | 27 | 46 | 77 | 86 |
| 16 | F | 67 | 2-door with B | 2 | 1,479.89 | 21 | 58 | 75 | 81 |
| 17 | M | 70 | 4-door sedan | 4 | 994.94 | 28 | 51 | 77 | 85 |
| 18 | F | 66 | 2-door with B | 2 | 1,373.83 | 20 | 43 | 65 | 70 |
| 19 | M | 71 | 4-door sedan | 5 | 1,373.83 | 19 | 48 | 76 | 84 |
| 20 | M | 69 | 4-door sedan | 4 | 1,170.74 | 21 | 52 | 77 | 86 |
| 21 | M | 71 | 4-door sedan | 4 | 1,394.88 | 22 | 57 | 77 | 83 |
| 22 | F | 61 | 4-door sedan | 4 | 1,304.93 | 18 | 59 | 76 | 84 |
| 23 | M | 71 | 2-door with B | 2 | 1,444.67 | 20 | 51 | 69 | 76 |
| 24 | F | 67 | 4-door st wag | 5 | 1,416.58 | 22 | 47 | 72 | 81 |
| 25 | F | 62 | 4-door sedan | 4 | 1,291.05 | - (12)*** | 48 | 74 | 81 |
| **Average** | | | | | 1,274.81 | 21.75 | 50.13 | 73.21 | 80.38 |
| **Standard Dev** | | | | | 174.88 | 3.65 | 6.44 | 3.15 | 4.00 |

** Vehicle did not have B-pillars (not included in average)*
*** Reported by subject that peripheral view was limited by glasses (not included in average)*
**** Passenger-side mirror adjustment motor broken (not included in average)*

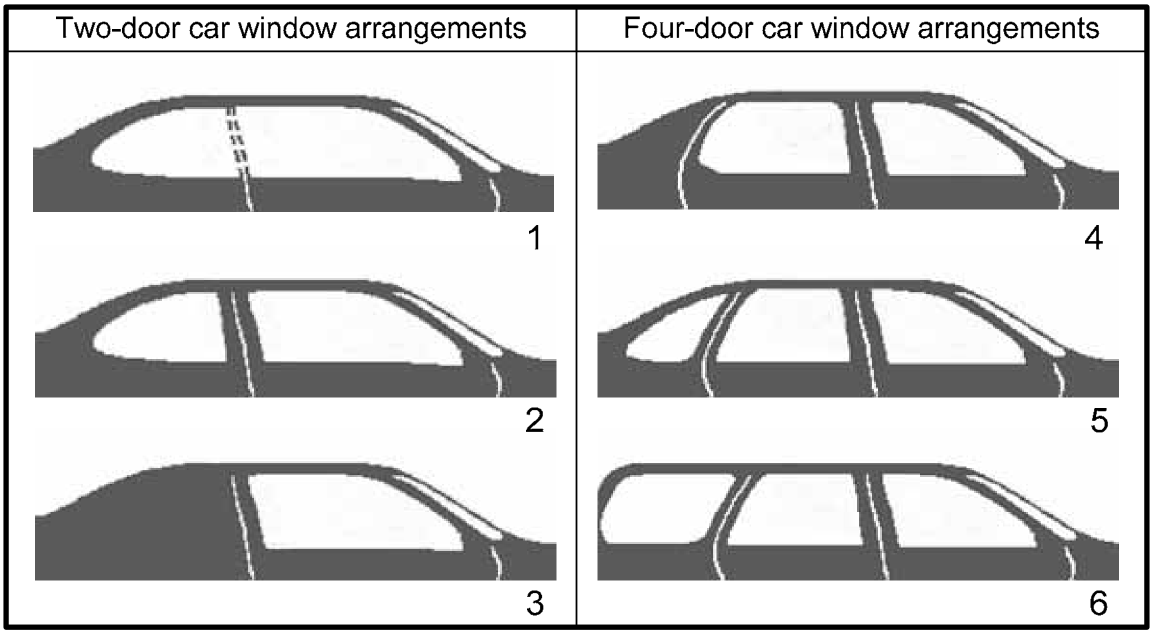


**Figure 24. Window arrangement types currently in use.**

As Table 9 shows, column 5 indicates the measured radius of curvature of the vehicles' mirrors in millimeters. The various angles associated with visibility appear in the last four columns of the table (columns 6 through 9).

Average data have been converted to a drawing as shown in Figure 25. The figure shows that there is a minor blind area occurring as a result of the B-pillar, when it is present. This blind area averages a width of slightly more than 7 deg. In addition, there is a larger blind area between the direct view limit and the mirror outer limit. Using all of the data, this blind spot averages 28.4 deg. It is conceivable that a driver could miss a vehicle in the adjacent right lane owing to the magnitude of this blind area. In addition, it is certainly the case that a driver could miss a vehicle merging into the adjacent right lane from an entry ramp or from a second lane on the right.

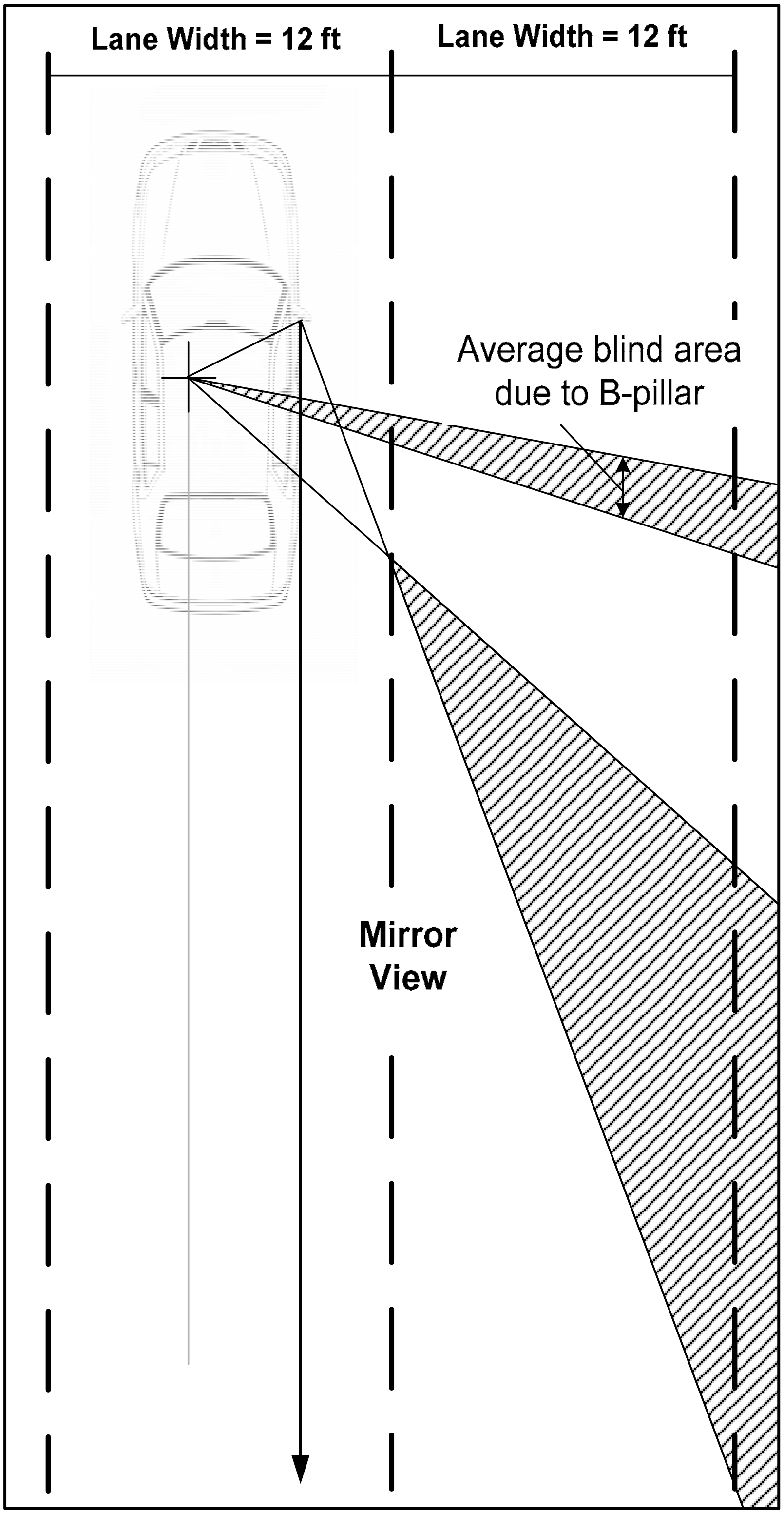


**Figure 25. Blind areas based on average data, passenger side.**

Because of the variation in mirror radius of curvature, the data were subdivided into two categories: those having radii of curvature between 900 and 1,100 mm, and those having radii of curvature between 1,300 and 1,500 mm. Six rows of data fell in the 900 to 1,100 mm category and 16 rows of data fell in the 1,300 to 1,500 mm category. Accordingly, two additional plots were made, showing the blind areas for each category. Figure 26 shows the results for mirrors in the 900 to 1,100 mm range, while Figure 27 shows the result for the 1,300 to 1,500 mm range. There is only the slightest difference between the plots. The shorter radius mirrors result in a blind area that is perhaps 2 deg smaller than that for all data, while the longer radius mirrors result in a blind area that is perhaps 1 degree larger than that for all data.

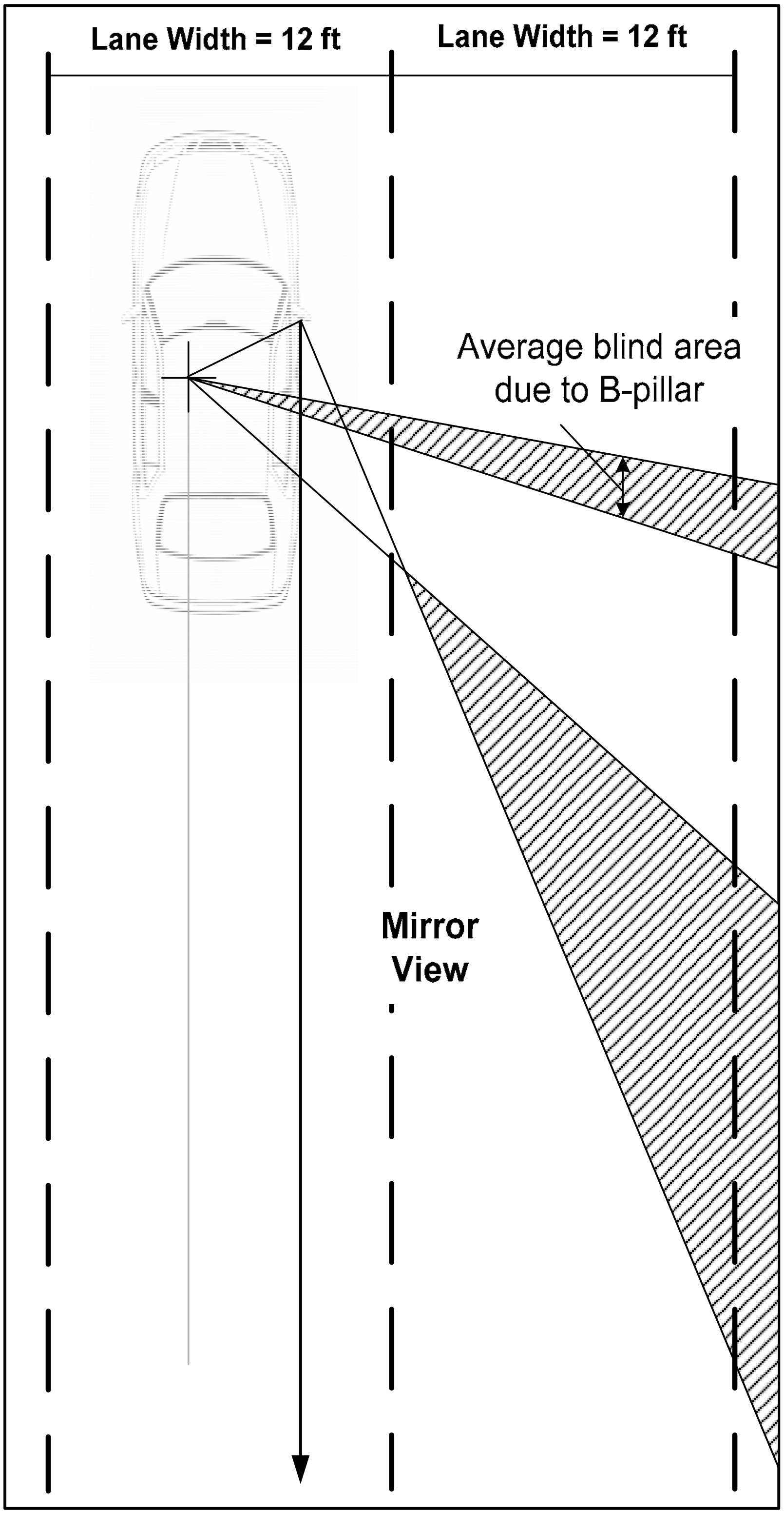


**Figure 26. Blind areas for mirrors with radii of curvature between 900 and 1,100 mm, passenger side.**

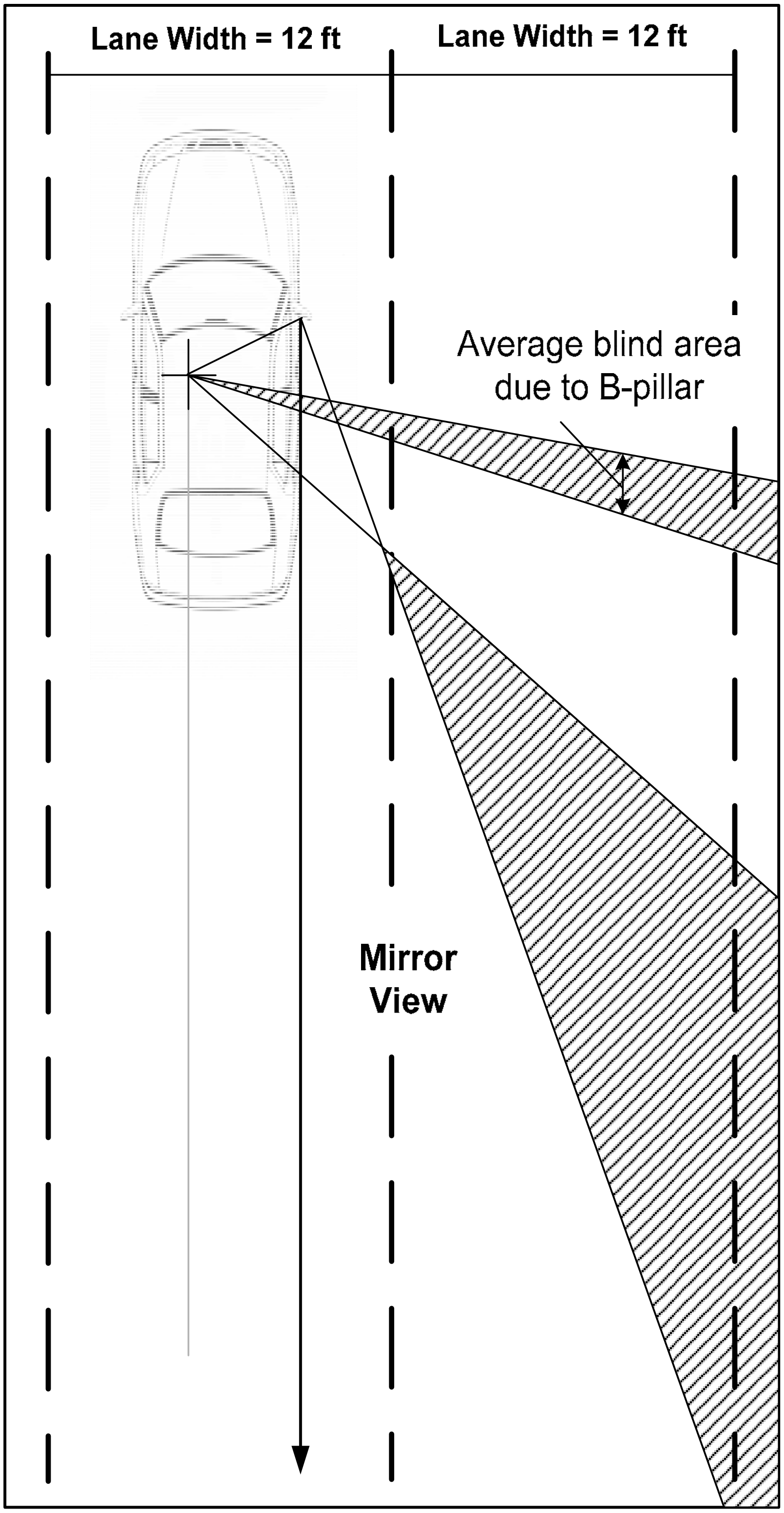


**Figure 27. Blind areas for mirrors with radii of curvature between 1,300 and 1,500 mm, passenger side. (This figure also represents the C14 mirror.)**

The average angle of mirror coverage for the mirrors in the 1,300 to 1,500 mm radius category indicates that there is coverage of approximately 20.8 deg. Comparing this value with the angular coverage for the C14 mirror in Table 8 shows that there is virtually no difference; that is, the mirror has 21 deg of coverage. This means that no correction is necessary in determining the projected coverage for the other mirrors. In addition, Figure 27 represents the angular coverage for the C14 mirror. Drawings for the C20, the A20, and the A14 mirrors can then be obtained by using the angles in Table 8 without modification. The results are shown in Figures 28, 29, and 30 for each of the other three mirrors.

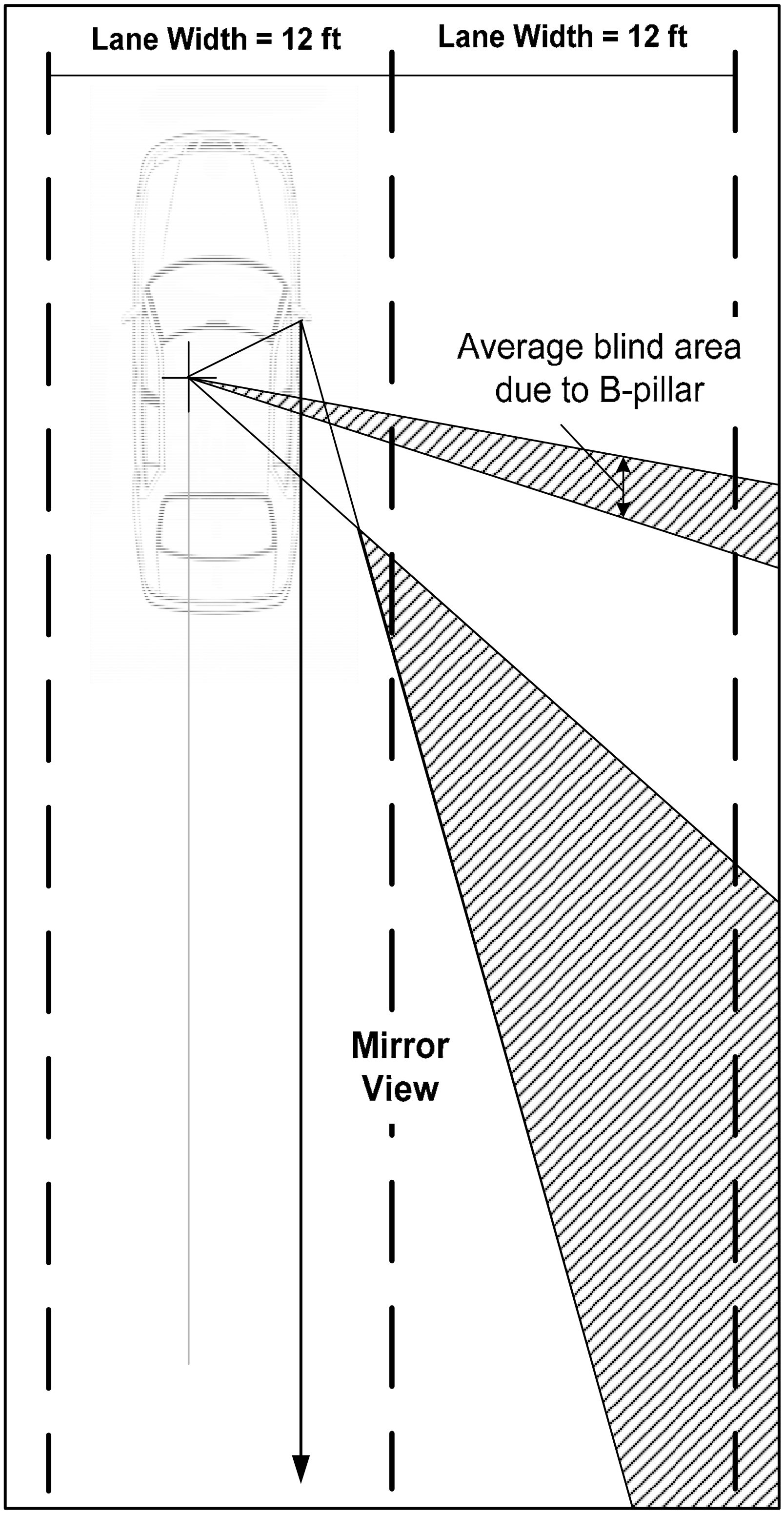


**Figure 28. Projected blind areas for a C20 mirror mounted on the passenger side.**

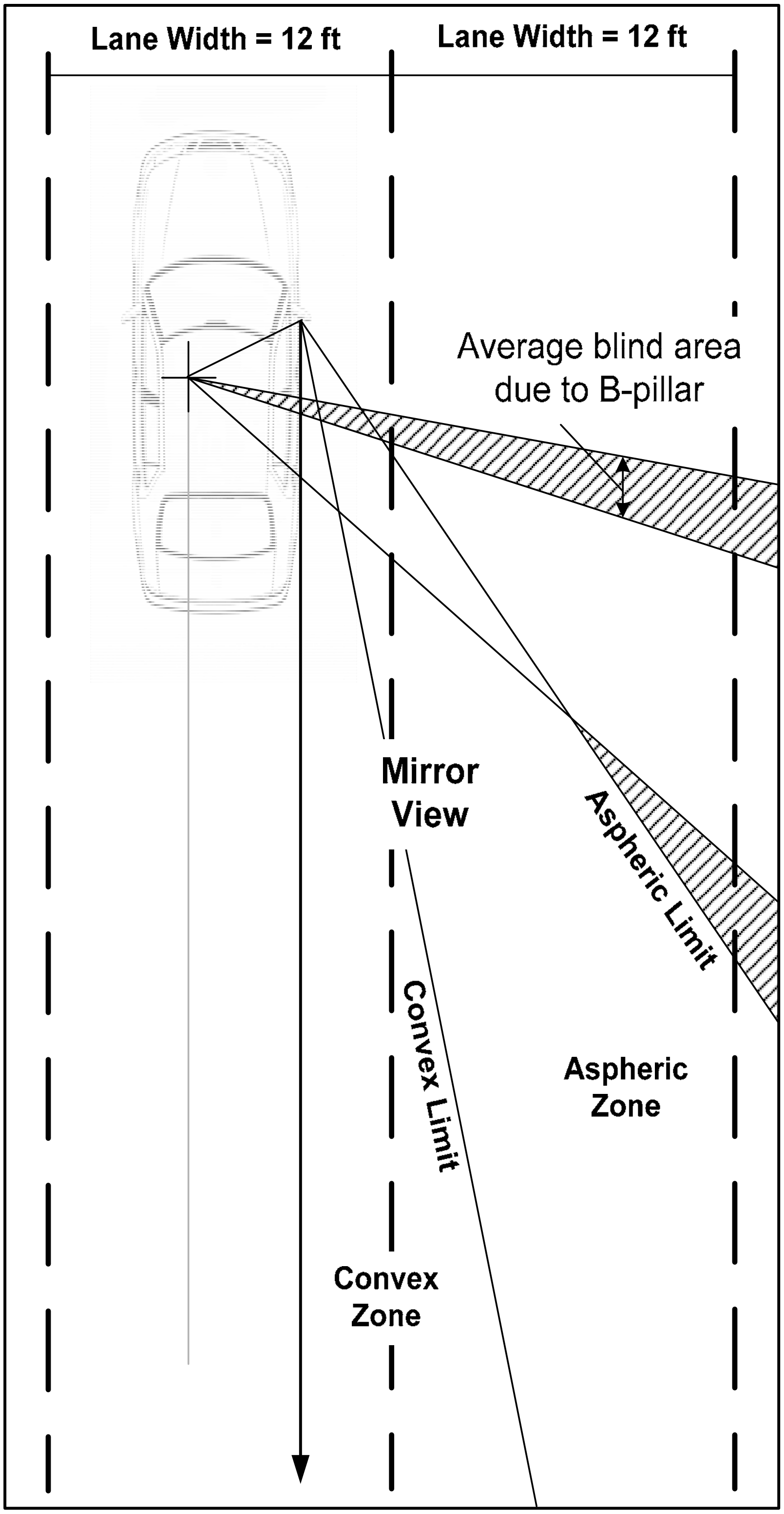


**Figure 29. Projected blind areas for an A20 mirror mounted on the passenger side.**

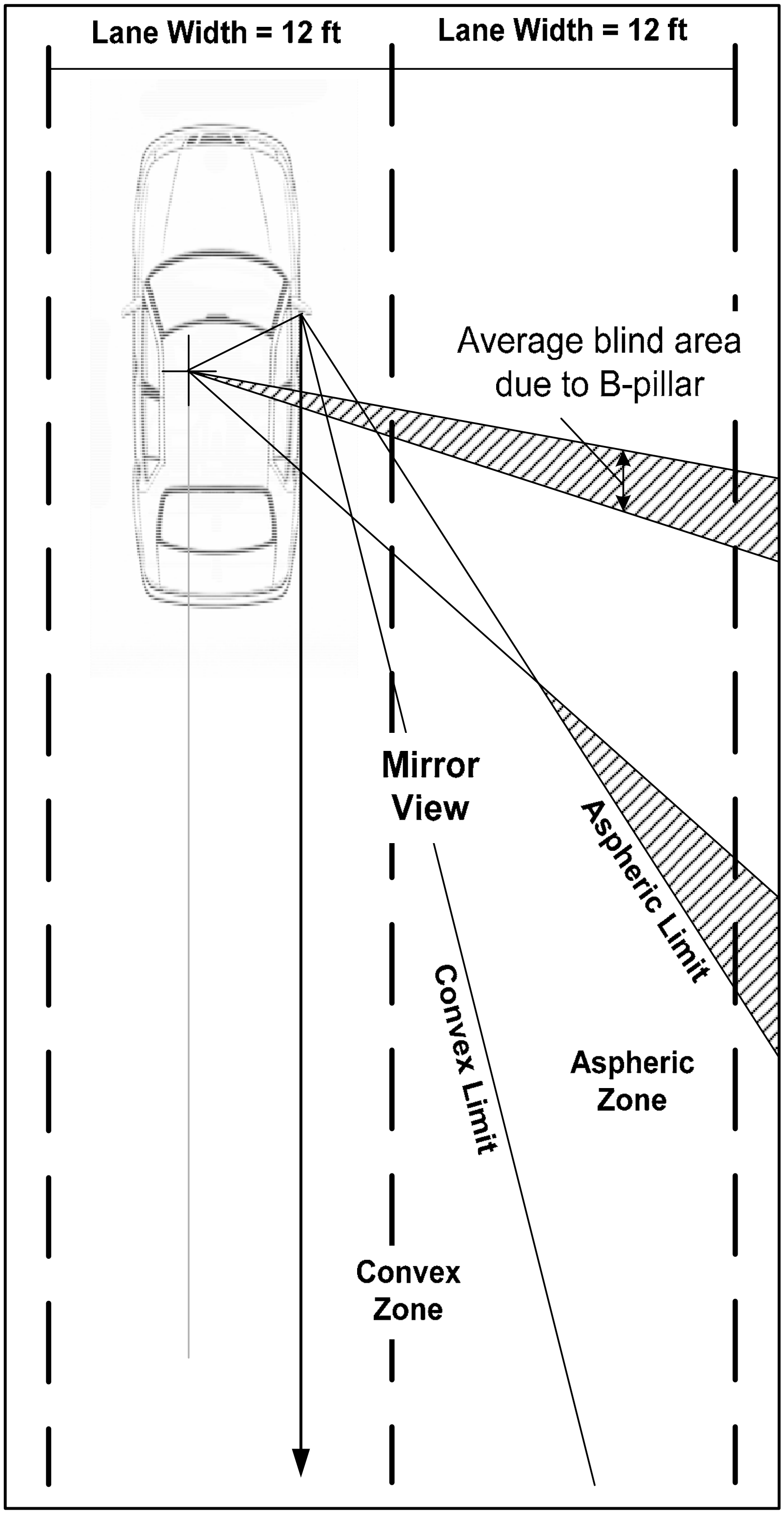


**Figure 30. Projected blind areas for an A14 mirror mounted on the passenger side.**

**Conclusions**

The data depicted in Figures 27 through 30 show very clearly that the A20 and A14 mirrors nearly eliminate the blind area to the right rear on the passenger side of the vehicle. However, the undistorted region, that is, the region in which the mirror is convex, is smaller than for standard convex mirrors. Consequently, there is a tradeoff wherein increased coverage comes at the cost of a larger region in which the image is distorted. Note specifically that the blind areas in Figures 27 and 28, corresponding to the two convex mirrors, are quite large and could hide a vehicle under certain circumstances. All of these results are as expected.

In comparing the A20 with the A14, there is very little difference in the total angle of coverage. However, the A20 has less minification in its convex region, and the convex region is somewhat smaller. Here again, a tradeoff exists between the size of the region and the amount of minification. For an aspheric mirror, as the convex-region radius of curvature increases (less minification), the size of the convex region decreases.

# CHAPTER 16: STATIC EXPERIMENT INVOLVING DISTANCE ESTIMATION USING REAR-VIEW MIRRORS

## Introduction

Estimation of apparent distance is an important aspect of rear-view mirrors. Drivers are believed to use their mirrors for two related purposes: object detection and distance estimation. Object detection usually involves determining whether another vehicle is present in a given direction, relative to the driver's vehicle. Distance estimation is then used to determine whether or not a conflict might occur, should the driver choose to maneuver in the direction of the object. Relative speed is also important in making such decisions, but this topic is examined later in regard to dynamic tests.

Previous studies have been carried out with various types of mirrors to assess the driver's ability to use these mirrors effectively. The most closely related was that performed by Flannagan, Sivak, Schumann, Kojima, and Traube (1997). They used flat and convex mirrors (1,400 mm radius of curvature) on both the driver and passenger side of the vehicle. They showed that mathematical models of apparent distance based on object angular subtense at the eye did not provide any degree of accuracy in predicting driver's estimation of distance. Apparently, other factors of human perception and cognition come into play. More will be said about this in the discussion section of this chapter.

Chapter 7 showed the relationship between convex mirror curvature and minification factor. This factor is defined as the ratio of angle subtended at the eye for a given convex mirror, divided by the angle subtended at the eye for an equivalent flat mirror. In general, minification is less than unity because convex mirrors create images that are smaller than those produced with flat mirrors. As a consequence of this minification, passenger-side convex rear-view mirrors in the United States contain the legend "objects in mirror are closer than they appear."

Because of possible confusion regarding distance estimation, a static experiment was planned and conducted independently at VTTI. Its purpose was to determine what types of distance estimates were likely to occur as a function of the type of mirror used. This experiment was intended to compare flat and convex mirrors. The reason for not including aspheric mirrors in this test was that it is unlikely that drivers would try to estimate distance using the aspheric region of aspheric mirrors. More likely, if drivers were to use aspheric mirrors to estimate distance, they would use only the spherical portion. Two different convex mirrors were used to provide some range within the data. Only the driver side was tested, because drivers would be less likely to be relying on cognitive compensation on this side of the vehicle. The experiment was set up using technically trained individuals. It was hypothesized that such individuals would be better at expressing distance estimates than individuals who were not technically trained.

## Procedure

Three driver-side mirrors were selected for the experiment. The first was a flat mirror (F), the second was a convex mirror having a nominal radius of curvature of 2,000 mm (C20), and the third was an aspheric mirror with a convex portion having a nominal radius of curvature of 1,400 mm (A14). The three mirrors were from a Saab 9-5 vehicle, and the subjects sat in the driver's seat of this type of vehicle (Figure 31). Since the 1,400 mm mirror had an outer aspheric portion, this portion was masked so that only the spherically convex inner portion could be used to estimate distance. For consistency, the two remaining mirrors were also masked in exactly the same way. Thus, the three mirrors were identical except for their radii of curvature. It should be noted that the amount of curvature was unnoticeable without careful examination. All three mirrors gave the appearance of being flat. With the masking in place, each mirror surface was 5.0 in (12.7 cm) wide by 3.88 in (9.9 cm) high.

It must be emphasized in reading the results of this experiment that, although one of the mirrors used was aspheric, only the convex portion was used. Therefore, the findings only apply to the following three types of mirrors: flat, convex with 2,000 mm radius of curvature, and convex with 1,400 mm radius of curvature.

Drivers in the United States do not ordinarily encounter any mirror other than a flat one on the driver side of light vehicles. Therefore, they ordinarily have no experience with convex mirrors on the driver side. By using driver-side mirrors, it was believed that drivers could better estimate apparent distance to an object based on optical aspects, as opposed to experience-related aspects that would ordinarily enter into passenger-side mirror judgments. Estimates based on optical aspects were of primary interest in this experiment.

Since flat mirrors provide "unit magnification," that is, they provide an image size that is identical to object size, it would be expected that such mirrors should produce the best estimates of actual distance. The minification factor of a flat mirror is unity, suggesting that the apparent distance should be the sum of the nominal eye-to-mirror distance and the mirror-to-object distance.

Eighteen individuals with technical training were selected for the experiment. All were employees of VTTI, and all held a valid driver's license. Technical training was considered to be demonstrated by having completed at least two years of college-level work in any field in which quantitative science or engineering, and mathematics are routinely used.

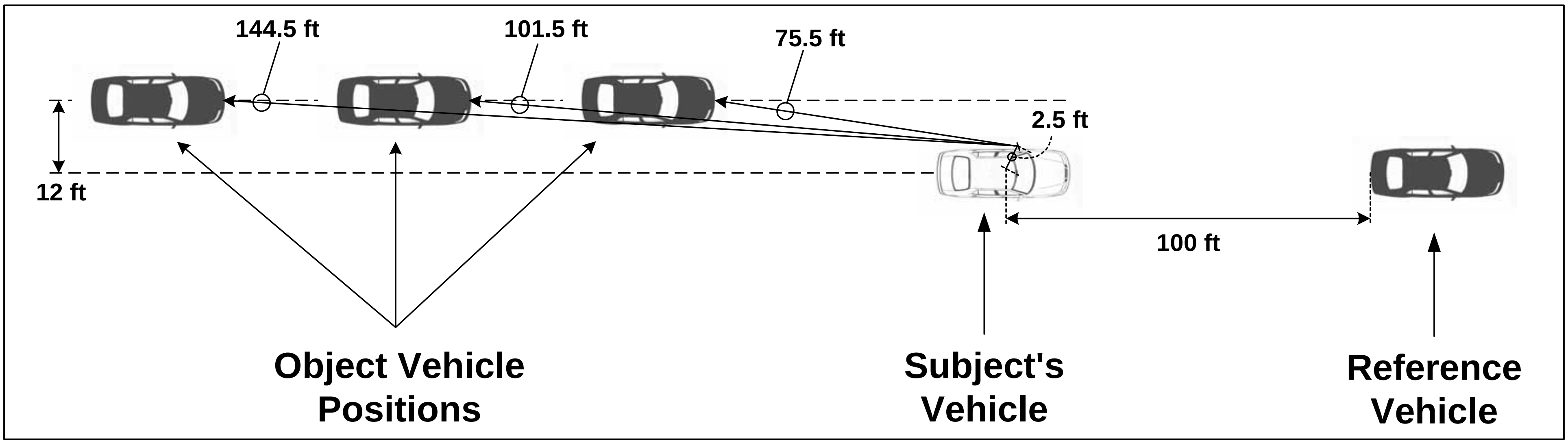


**Figure 31. Vehicle arrangement for distance estimation experiment. (Note that the drawing is not to scale.)**

## Data Gathering

The driver sat in the driver's seat and adjusted it to a comfortable position. Thereafter the first mirror was put in place. Mirrors were attached using "hook-and-loop" adhesive-backed fastening material, as previously explained (Figure 16, Chapter 13). All protrusions from the back of the test mirrors had been machined away so that the mirrors would lay flat against the factory-installed underlying mirror. After the first mirror was put in place, the driver quickly adjusted the mirror until the object vehicle to the rear was in full view. All estimates were made with the reference vehicle (to be explained), driver's vehicle, and object vehicle in static positions (Figure 31).

The experiment took place in a large gravel parking lot. Consequently, distance had to be judged largely on the basis of the object vehicle being viewed in the mirror. The background behind the object vehicle included a fence that ran diagonally behind the object vehicle and tall trees in the distance. These environmental scene aspects were selected because they did not appear to provide strong distance cues.

A so-called reference vehicle was placed 100 ft (30.5 m) in front of the driver's nominal eye position. The driver was made aware of the distance to the reference vehicle, as indicated in the subject instructions shown in Appendix A. The reference vehicle was not the same make of vehicle nor was it exactly the same shape as the object vehicle. However, overall, it was approximately the same size of vehicle.

The driver was asked to look down into his or her own vehicle until the object vehicle had been driven into place to the rear, in what would have been the adjacent left lane. While this was being done, the mirror to be used for the test was installed. During this period, the driver wore hearing protection earmuffs to reduce the possibility that sound cues from the object vehicle could be used to help estimate distance. As an additional precaution, the interior rear-view mirror and the passenger-side outside rear-view mirror of the driver's vehicle were aimed downward so that they could not be used. When instructed to do so, the driver then looked into the driver-side mirror and adjusted it if necessary using remote control switches. The driver then observed the object vehicle, but could also look forward at the reference vehicle if desired. The driver then gave an estimate of apparent distance to the object vehicle, which was recorded by the experimenter. A maximum of 10 s was permitted in making the estimate, once mirror adjustment (if any) had been made. The driver gave one estimate for each of the three mirrors and corresponding distances; that is, three estimates in total. The object vehicle was moved to a different location and the mirror was changed for each estimate. Data gathering took place in non-rainy, daylight conditions.

## Experimental Controls

As stated earlier, the distance to the reference vehicle was 100 ft (30.5 m). This distance was measured from the driver's nominal eye position to the rear bumper of the reference vehicle. In positioning the object vehicle to the rear, the distance was measured from the driver's nominal eye position relative to the mirror, added to the distance from the mirror to the front bumper of the object vehicle. (Correction was not made for the driver's seat adjustment, which might have added or subtracted approximately 2 in for the largest or the smallest driver, respectively.) To prevent "learning" of the correct object distance, three different distances were used. They were x1 = 78 ft (23.8 m), x2 = 104 ft (31.7 m), and x3 =147 ft (44.8 m).

Note once again that each distance was the sum of the distance from the driver's eyes to the mirror and the distance from the object vehicle to the mirror. The distance from the driver's eyes to the mirror was approximately 2.5 ft (0.76 m). Thus, for the 78 ft distance, the distance from the object vehicle to the mirror was 75.5 ft (23.0 m). This approach was used because, for a flat mirror, it provides the same total distance as a direct view. For example, an object at 97.5 ft (29.7 m) from the mirror would appear to have exactly the same height as the same object in direct view at 100 ft (30.5 m) from the eyes. Drivers were told ahead of time that each object distance could be a whole round-number distance "such as 95 ft" or a whole non-round-number distance "such as 97 ft." In other words, any whole number distance might be used.

There were six possible orders of mirror presentation. Three drivers experienced each given order of mirror presentation, resulting in the use of eighteen drivers in all. For a given mirror presentation order, the first driver estimated x3, then x2, then x1. The second driver estimated x1, then x3, and then x2. The third driver estimated x2, then x1, and then x3. This order was repeated for each group of three drivers, that is, for each mirror presentation order.

Additional instructions to the driver emphasized not trying to "figure the experiment out," but rather, to just give the estimates based on what the driver was seeing in the outside rear-view mirror. These instructions were used to help avoid the curiosity aspects of behavior which sometimes accompany the use of technically trained subjects.

### Analyses and Results

Initially, a 3-by-3 analysis of variance was performed on each dependent variable. The independent variables were Mirror Type (F, C20, and A14) and Distance (x1 = 78 ft, x2 = 104 ft, and x3 = 147 ft). The dependent variables were: Estimated Distance, Error, Absolute Error, Percent Error, and Absolute Percent Error (in distance estimates). The significant results are summarized in Table 10.

**Table 10. Domain of significance for the two-way analysis for the independent variables of mirror type and (actual) distance.**
**(Means with a common underline do not differ significantly, $\alpha = 0.05$.)**

| | | |
|---|---|---|
| **Estimated Distance** | | |
| Distance | | $F_{(2,45)} = 21.9$, $p < 0.0001$ |
| Mirror Type by Distance | | $F_{(4,45)} = 3.24$, $p = 0.0202$ |
| | Actual Distance | 78    104    147 |
| | Estimated Distance | 62.5    83.5    117.5 |
| | | |
| **Error in Distance** | | |
| Mirror Type by Distance | | $F_{(4,45)} = 3.24$, $p = 0.0202$ |
| **Percent Error in Distance** | | |
| Mirror Type by Distance | | $F_{(4,45)} = 3.79$, $p = 0.0096$ |

The results of the analysis of variance for Estimated Distance indicated a significant main effect as a function of Distance and a significant interaction between mirror type and distance. None of the four error-type dependent measures exhibited any significant main effects. However, there were significant interactions between mirror type and distance for rrror and for Percent error. Also, for the main effect of estimated distance, Tukey HSD tests were performed comparing performance at each level of actual distance. The results, shown in Table 10, indicate that the subjects provided significantly different values at each actual distance ($\alpha = 0.05$). It should be noted that the mean value of the estimates increased with the actual object distance. However, the mean values at each level were below the actual distances; that is, they were underestimates.

To pursue the interactive effects in the two-way analyses further, several one-way analyses of variance were performed as a function of actual distance. These were intended to show how the various mirrors interacted with distance. The results of these analyses are presented in Table 11.

**Table 11. Domain of significance for the one-way analyses as a function of (actual) distance.**
**(Means with a common underline do not differ significantly, $\alpha = 0.05$.)**

| | | |
|---|---|---|
| **Estimated Distance** | | |
| Flat Mirror (F) | | $F_{(2,15)} = 5.84$, $p = 0.0133$ |
| | Actual Distance | 78 104 147 |
| | Estimated Distance | 55.8 80 105 |
| | | |
| Convex Mirror (C20) | | $F_{(2,15)} = 10.73$, $p = 0.0013$ |
| | Actual Distance | 78 104 147 |
| | Estimated Distance | 75.8 63.3 132.5 |
| | | |
| Aspheric Mirror (A14) | | $F_{(2,15)} = 11.95$, $p = 0.0008$ |
| | Actual Distance | 78 104 147 |
| | Estimated Distance | 55.8 107.2 115 |
| | | |
| **Error in Estimated Distance** | | |
| Aspheric Mirror (A14) | | $F_{(2,15)} = 3.81$, $p = 0.0460$ |
| | Actual Distance* | 78 147 104 |
| | Estimated Distance | 22.2 32.0 -3.2 |
| * Note order change | | |

As Table 11 shows, these analyses resulted in significance for estimated distance for each mirror type. Post hoc tests are also included in the table and show which mean values differ significantly using the Tukey HSD test. The mean values for estimated distances are plotted in Figure 32 as a function of actual distance. The plot shows that the significant effects are a result of the generally increasing estimates as a function of actual distance. The plot also shows the true distance. Clearly, as indicated earlier, the mean values are generally *below* the true distances, indicating a general underestimation of distances for the three mirror types. Only the A14 mirror at 104 ft resulted in a slight mean overestimation (107.2 ft).

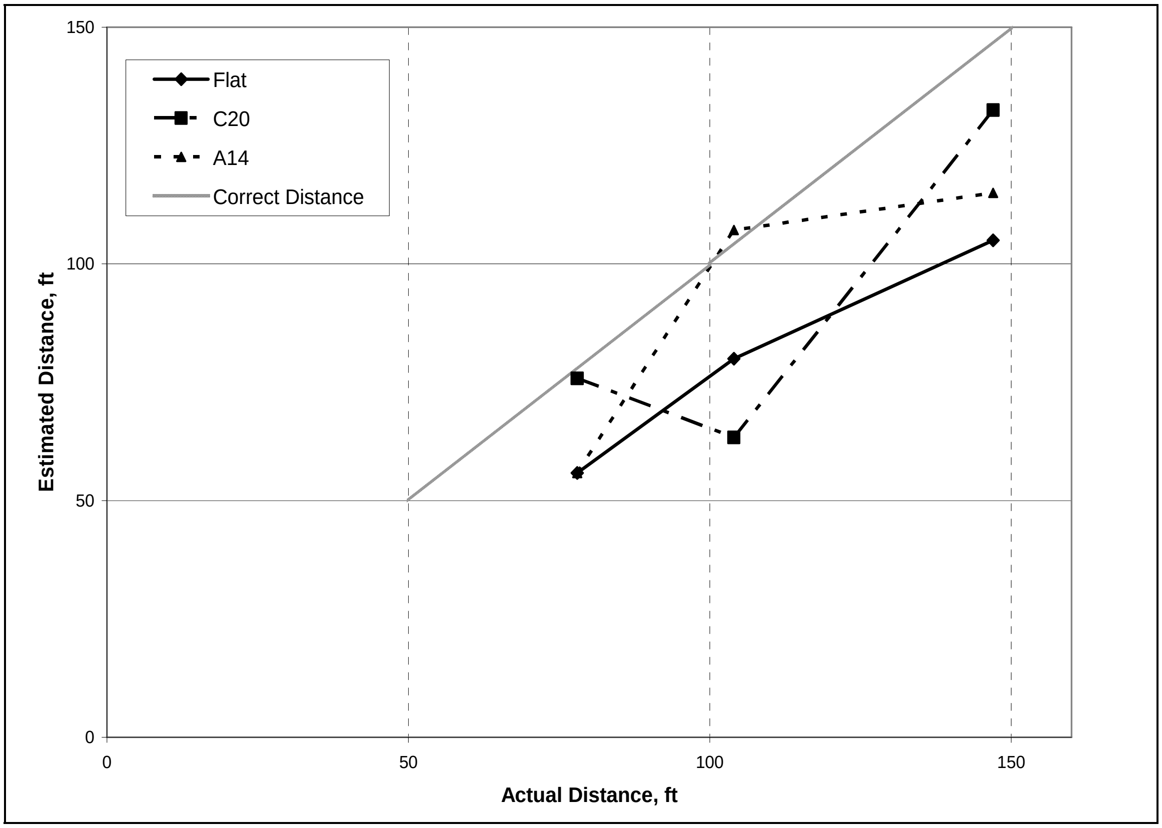


**Figure 32. Mean estimated distance values compared with actual distance values.**

The only other significant result in the one-way analyses is that of error for the aspheric mirror (Table 11). This result is also for the A14 mirror and appears to be a result of the slight overestimation at the 104 ft distance, as compared with the underestimation at the other distances.

Because overestimation of distance represents a potentially dangerous situation, in that the object in the mirror would be closer than the driver's estimate, an additional analysis was performed on individual occurrences. Table 12 shows the raw numbers of overestimation occurrences as a function of mirror type and actual distance. To test for reliable differences, a Fisher's exact test was applied to the data. The result was found not to be significant ($p = 0.1342$). Consequently, overestimation was not demonstrated in this experiment to be related to mirror type or the actual object distance.

**Table 12. Raw numbers of overestimates for each mirror type.**

| Number of Overestimates | | | |
|---|---|---|---|
| | 78 | 104 | 147 |
| Flat | 0 | 0 | 1 |
| C20 | 4 | 0 | 1 |
| A14 | 1 | 3 | 1 |

## Discussion and Conclusions

The results of the experiment are surprising, but they are also consistent with previous work. The greatest surprise is that the drivers did *not* consistently overestimate distance using the two convex mirrors (Figure 32). From optics, we know that the angle of the image subtended at the eyes for the two convex mirrors is substantially smaller than for a flat mirror. It would be reasonable to assume that drivers would therefore say that the object was substantially farther away than it actually was. This did not occur. Instead, drivers generally *underestimated* the distance to the object vehicle. The exception was for the A14 mirror at an actual object distance of 104 ft. The mean estimate for this mirror at this distance was 107.2 ft, probably not enough to be considered dangerous and really quite close to the actual distance. Flannagan, Sivak, Schumann, Kojima, and Traube (1997) observed exactly the same phenomenon. Their Figure 7 shows that drivers underestimated actual distance by about 10 percent at 20 m and by about 5 percent at 30, 40, and 50 m, using a convex mirror with a 1,400 mm radius of curvature. Such a mirror corresponds almost exactly to the A14 mirror (with masking) as used in the current experiment.

For the flat mirror the experimental results also show consistent underestimation (Figure 32). Apparently, even with a vehicle parked 100 ft (30.5 m) away and used as a reference, drivers consistently underestimated the distance to an object vehicle to the rear. It seems particularly surprising that even at the 104 ft distance where the image in the mirror was approximately the same size as the reference vehicle, the drivers underestimated this distance by about 24 ft. It is therefore quite clear that other behavioral aspects are entering the situation. Again, the results are consistent with those of Flannagan, Sivak, Schumann et al. (1997). Their Figure 7 shows an underestimation of about 27 percent to 29 percent across an object range of 20 to 40 m and an underestimation of 20 percent at 50 m.

What could be causing these unusual results? First, there are several visual aspects that could be contributing to the results, including vergence, accommodation, framing, and possibly background or scene aspects around the object. Second, there is the possibility that drivers are aware of how dangerous it is to overestimate distance in rear-view mirrors, and they may have developed coping strategies that involve conservative estimates of distance. The human visual/cognitive process is a complex one, and a precise explanation remains to be found.

The current experiment used a small sample and did not find a significant effect of mirror type. However, if the effect had been substantial, the experiment would have demonstrated significance. It should therefore be concluded that the effect of mirror type across the range tested does *not* have a substantial effect on distance estimation. It may have a minor effect, but it is nowhere near as large as would be predicted on the basis of image angle subtended at the eye. Furthermore, image angle at the eye would produce consistent and large overestimation of actual distances for convex mirrors, whereas this experiment shows that underestimation ordinarily occurs.

As indicated, the results of the Fisher exact test for number of occurrences of overestimation did not indicate significance. Consequently, it can be concluded that over-estimation occurrences are not a strong function of mirror type or actual distance, if at all. It is possible that with a larger sample size a mirror effect might have been demonstrated. Figure 32 suggests that the means of the estimated values for the convex mirrors are a bit closer to the correct distance than are the estimated values for the flat mirror. If this is the case, then given the same variations about the means, the convex mirrors would produce more overestimates. Table 12 is consistent with this observation, in that there was one overestimate for the flat mirror and five for each of the convex mirrors.

As mentioned earlier, the Flannagan, Sivak, Schumann et al. (1997) results do show that the convex mirror produced mean estimates closer to the true distance than did the flat mirror. It follows then that the convex mirror would produce more overestimates because of variation about the means.

The results of this experiment can be summarized as follows:

- Most of the time drivers underestimate distance to objects using exterior driver-side rear-view mirrors.
- Models of distance estimation relying solely on subtended angle of the image, which would result in overestimation of distance to objects when using convex mirrors, are not good predictors of drivers' distance estimates.
- Drivers using flat mirrors (which have unit magnification) consistently underestimate the distance to objects appearing in these mirrors, even when there is a reference vehicle in the forward view for which the true distance is known.
- Whether the driver uses a flat or a convex mirror to estimate distance has at most a second order effect on distance estimation. This experiment, although limited in statistical power, did not find a significant main effect of mirror type.
- Overestimates of distance can be considered to be hazardous. The statistical test for number of overestimates occurring as a function of mirror type and actual distance was not significant. However, the Flannagan, Sivak, Schumann, et al. (1997) results suggest that a convex mirror is more likely to have overestimates of distance. Such results are consistent with the entries in Table 12 of the current study.
- A full explanation for the distance estimation phenomenon occurring in the current study (as well as several previous studies) remains to be found. This would serve as an excellent dissertation topic.

## CHAPTER 17: STATIC SUBJECTIVE HEADLIGHT GLARE EXPERIMENT

### Introduction

The purpose of this static experiment was to compare the rated discomfort glare of various rear-view mirrors in a situation very much like that encountered while driving. This test was intended to provide a clear-cut subjective assessment of the glare to which drivers might be exposed while using various mirrors. The tests were performed using an actual automobile with the outside test mirrors mounted over the usual mirrors. All tests took place in the late fall and early winter shortly after dark. The results provide a direct within-subject comparison of the various types of mirrors.

In this experiment, the subject's vehicle (Saab 9-5) was parked in the center of a given lane of a large black-topped area. The area was private and out of traffic. Lane lines extended to the rear of the vehicle. A second (confederate) vehicle (Chevrolet 2500 extended-cab pickup truck with newly installed, but otherwise standard, rectangular sealed-beam halogen headlamps #H6054), with its high-beams on, was driven to various positions behind the subject's vehicle (Figure 33). For evaluation of the passenger-side outside mirrors, the confederate vehicle was located in the right adjacent lane, and for evaluation of the driver-side outside mirrors, the confederate vehicle was located in the left adjacent lane. A single interior rear-view mirror was also evaluated with the confederate vehicle located behind and in the same lane as the subject's vehicle.

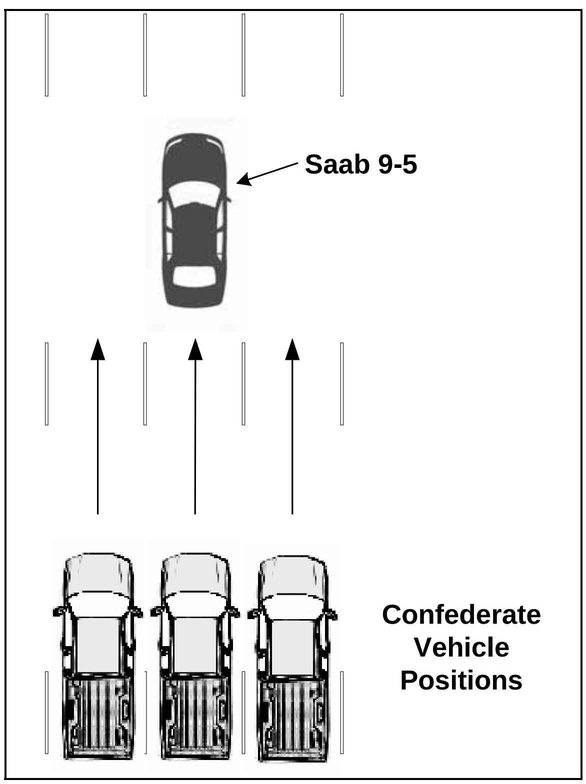


**Figure 33. Subjective Glare Assessment experimental arrangement.**

The subject rated the glare using a modified deBoer scale, with the confederate vehicle stopped at the various fixed positions. The scale is shown in Figure 34. It was carefully explained to each subject prior to the evaluations. The scale was evolved from a discomfort glare scale developed by Wierwille, Lee, and DeHart (2003) in connection with automotive rear lighting. It is important to note that the scale numerical values were the reverse of those used in the original deBoer scale. High numerical values in the new scale represent high levels of discomfort glare.

**Discomfort Glare Rating Scale**

Discomfort glare is glare that a person finds uncomfortable to a greater or lesser degree. Please rate your level of discomfort glare for the current situation by selecting the number from the following scale that most closely matches your perception of the discomfort glare level (note that you may select a value half way between descriptions, if you wish).

DISCOMFORT GLARE LEVEL

| General Description | Precise Description | Viewer's Reaction |
|---|---|---|
| Acceptable | 1. Not noticeable | There is no glare in this situation, and I could look at it for any length of time with no discomfort. |
| | 2. Just noticeable | There is a small amount of glare in this situation, but I could look at it for a long time without discomfort. |
| | 3. Satisfactory | The level of glare is tolerable for this situation. I could look at it for quite a while without discomfort. |
| Borderline | 4. Not quite satisfactory | The level of glare is a little bothersome. I would not want to look for more than 20 to 40 seconds. |
| | 5. Just acceptable | The level of glare is at the border of acceptability. I would not want to look for more than 10 to 20 seconds. |
| | 6. Bordering on disturbing | The level of glare is somewhat disturbing. I would not want to look for more than 5 to 10 seconds. |
| Undesirable | 7. Disturbing | The level of glare is definitely disturbing. I would want to look away in less than 5 seconds. |
| | 8. Nearly unbearable | The level of glare is nearly unbearable. I would want to look away in less than three seconds. |
| | 9. Unbearable | The level of glare is definitely unbearable. I would want to look away after a glance. |

**Figure 34. Discomfort glare rating scale.**

There were two groups of subjects: younger (age 18 to 35) and older (age 66 to 71). It was recognized that older subjects may be more sensitive to discomfort glare, so it was deemed important to include them in the experiment.

**Procedure**

The mirrors to be evaluated were placed over the existing outside rear-view mirrors using hook and loop adhesive backed tape (as previously explained, Figure 16, Chapter 13). All protrusions from the backs of the test mirrors had been machined away, so that the mirrors would lay flat against the factory-installed underlying vehicle mirrors.

Once a set of outside rear-view mirrors had been put in place, the subject, who was sitting in the driver's seat, adjusted the mirrors horizontally until the inside edge provided a reflection that was just tangent to the side of the subject's vehicle. The subject also adjusted the mirrors vertically, so that the vertical center of each mirror view intersected a white square, 10 cm on each side and 60 ft (18.3 m) away from the mirrors on the subject's vehicle. The white square was centered in the corresponding lane at a point 35.5 in (90.2 cm) above the pavement, that is, the height of the headlamps of the pickup truck. A co-experimenter illuminated the white square, which was mounted on a stick, with a flashlight at the designated point to help the subject during the aiming procedure. The distance was selected as being typical for mirror aiming. This aiming procedure placed the truck's headlamps within view of the driver's eyes, except possibly at the near locations of the truck.

Four different exterior mirrors were evaluated on the driver side of the vehicle, and five different exterior mirrors were evaluated on the passenger side of the vehicle. Because of the difference in the number of mirrors to be evaluated, and also because a comparison was desired, the glare induced by the factory-installed interior center mirror was also evaluated. This mirror was included in counterbalanced order with the four driver-side exterior mirrors, thus creating a five mirror set involving the combination of driver-side mirrors and interior mirror. It should be noted that the interior mirror was conventional in that it did *not* have an electro-chromic surface. It was used in the darkened (nighttime) setting.

The various mirrors used in the experiment are shown in Table 13. (Greater detail in the specification of the outside rear-view mirrors can be found in Tables 2, 3, and 4 of Chapter 12.) Note that the interior center mirror is grouped with the driver-side mirrors, as discussed. All outside rear-view mirrors were "undarkened," that is, they had nearly identical silvered surface reflectances. No darkening films were used. As mentioned earlier, the interior mirror, designated I, was used in its darkened, that is, normal nighttime, position.

**Table 13. Mirrors used in the subjective glare experiment.**

| Driver's Side Mirrors | | | Passenger's Side Mirrors | | |
|---|---|---|---|---|---|
| **Description** | **Radius of Curvature** | **Designation** | **Description** | **Radius of Curvature** | **Designation** |
| Flat (Planar) | ∞ | F | Flat (Planar) | ∞ | F |
| Convex | 2,000 mm | C20 | Convex | 2,000 mm | C20 |
| | | | Convex | 1,400 mm | C14 |
| Aspheric | 2,000 mm* | A20 | Aspheric | 2,000 mm* | A20 |
| Aspheric | 1,400 mm* | A14 | Aspheric | 1,400 mm* | A14 |
| Interior Flat (Planar) | ∞ | I | | | |

* Designates nominal radius of curvature for convex portion

Mirror order of presentation to the driver was counterbalanced in accordance with the scheme shown in Table 14. The table is best explained by example. Subject Number 1 will be used to illustrate. After preliminaries, the subject, who was in the younger age group, was first exposed to the 2,000 mm aspheric mirror (A20) on the driver side. The confederate vehicle, with its headlamps on in the high beam position as previously mentioned, approached from the rear in the left adjacent lane. Seven stopped positions were used. The subject rated the glare at each position using the discomfort scale. The rearmost position was evaluated first, then the next rearmost, etc., until all seven positions had been evaluated.

**Table 14. Counterbalancing scheme.**
**(Columns marked with an asterisk were repeated at the end.)**

| Subject Number and Age Y | O | Presented First | Driver-side and Interior order ➔ * | | | | | Passenger-side order ➔ * | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 | D | A20 | I | C20 | F | A14 | F | C20 | C14 | A20 | A14 |
| 2 | 12 | P | I | C20 | F | A14 | A20 | A14 | F | C20 | C14 | A20 |
| 3 | 13 | D | C20 | F | A14 | A20 | I | A20 | A14 | F | C20 | C14 |
| 4 | 14 | P | F | A14 | A20 | I | C20 | C14 | A20 | A14 | F | C20 |
| 5 | 15 | D | A14 | A20 | I | C20 | F | C20 | C14 | A20 | A14 | F |
| 6 | 16 | P | F | C20 | A20 | I | A14 | C14 | A20 | C20 | F | A14 |
| 7 | 17 | D | C20 | A20 | I | A14 | F | A14 | C14 | A20 | C20 | F |
| 8 | 18 | P | A20 | I | A14 | F | C20 | F | A14 | C14 | A20 | C20 |
| 9 | 19 | I, then P | I | A14 | F | C20 | A20 | C20 | F | A14 | C14 | A20 |
| 10 | 20 | P | A14 | F | C20 | A20 | I | A20 | C20 | F | A14 | C14 |

Subject 1 was next exposed to the flat mirror (F) on the passenger side. The confederate vehicle again approached from the rear, but in the right adjacent lane, stopping at the same seven position distances from the mirror. At each distance, the subject evaluated the glare. After this, Subject 1 evaluated the mirrors in the order I (with the confederate vehicle approaching from the rear in the same lane as the subject's vehicle), C20 on the passenger side, C20 on the driver side, C14 on the passenger side, F on the driver side, A20 on the passenger side, A14 on the driver side, and finally, A14 on the passenger side. The presentation order is given in Table 14 by the first row and alternately selecting from the passenger side and then the driver side while moving to the right in the table.

Following completion of all the evaluations shown in the first row, the first driver-side presentation and the first passenger-side presentation were repeated, that is, A20 on the driver side and F on the passenger side. These repeated values were used in the data matrix. The first two sets of values obtained from the first two sets of evaluations were discarded. The purpose of this procedure was to help account for learning in the use of the rating scale and lack of previous exposure to the experimental setup.

Table 14 shows that for each younger subject (1 through 10) there was an identical protocol for one older subject (11 through 20). In all cases, the confederate vehicle approached from the farthest distance. Each odd-numbered subject evaluated a driver-side mirror first, while each even-numbered subject evaluated a passenger-side mirror first (with the exception of subjects 9 and 19, who evaluated the interior mirror first).

Several aspects of the interior mirror (I) evaluation require further explanation. First, the mirror was stowed in the downward-angled position when not under test for glare, so that it would not interfere with the outside rear-view mirror evaluations. Just prior to this mirror being evaluated, the mirror was aimed by having the subject center the mirror view horizontally in the center lane to the rear. It was also aimed vertically by centering it in exactly the same way using the white target illuminated by a confederate experimenter. The target was placed exactly 60 ft (18.3 m) behind the mirror at a height of 35.5 in (90.2cm), as with the side mirrors. Also, for the interior mirror, the confederate vehicle stopped for glare evaluations at the same distances (from the interior mirror) as were used in the evaluations of the side mirrors. However, at the closest distance the confederate vehicle was limited in how close it could get because of bumper interference. Thus, the closest distance for the interior mirror was approximately 2.5 ft (0.76 m) farther back than for the side mirrors. Since the trunk of the driver's vehicle tended to block the headlight glare at this distance, the change was believed not to have a major effect on the results. On completion of the glare evaluations for the interior mirror, the mirror was again angled downward so that it did not interfere with the remaining evaluations of the side mirrors to follow.

Several other aspects of the data gathering require additional explanation. First, the subject's vehicle was parked with the engine idling. The instrument panel lights and low-beam headlamps were turned on. These lights were used to approximate the level of illumination that a driver might encounter on a country road. Secondly, glare was evaluated with the side windows up, as they would ordinarily be used at night. The rear window of the vehicle was, of course, in place, creating a condition similar to that encountered in normal driving.

Drivers were instructed to look forward as if they were driving. When given a cue by the in-vehicle experimenter, they looked into the designated mirror. The subject was instructed to look for approximately 5 s, unless the glare was too uncomfortable. If so, the subject was to look away. The experimenter then showed the subject the rating scale and asked him or her to provide a rating, which the experimenter recorded. The scale was illuminated by means of the map light, which was located in the header area, 7 in (17.8 cm) from the top center of the windshield. The map light produced sufficient illumination to read the scale easily, but not so much as to require substantial re-adaptation to the forward outside scene. After completing the rating, the light was extinguished and the subject was instructed to look forward once again. The process continued with the confederate vehicle moving to the next position, or with the change of mirrors if all distances had been evaluated for the mirror set. In general, both passenger-side and driver-side mirrors were changed and adjusted at the same time. In the case of the interior mirror, as indicated, it was not changed but was merely adjusted.

It should be noted that the experimenter in the subject's vehicle and the co-experimenter in the confederate vehicle communicated by handheld radios. The experimenter gave instructions to the co-experimenter regarding when to move to the next position. Another co-experimenter in the rear seat of the subject's vehicle exited that vehicle when necessary and performed the task of changing the mirrors. This experimenter also set up the mirror adjustment target and illuminated it with a flashlight.

Finally, the seven distances used for evaluation were 10, 20, 30, 60, 90, 140, and 200 ft (3.05, 6.1, 9.2, 18.3, 27.4, 42.7, and 60.1 m). These distances were selected to provide a moderately comprehensive evaluation, representative of actual driving. As mentioned previously, the nearest distance for the case of the interior mirror was 12.5 ft (3.7 m). The distances were measured as distances projected into the lane of the approaching vehicle, from the corresponding mirror's surface to the headlamp position on the confederate vehicle. To position the confederate vehicle, the co-experimenter viewed duct-taped spots on the pavement that were positioned to be viewed with the confederate vehicle driver's door open slightly. The spots were in line with the vertical door edge when the vehicle was correctly positioned.

## Analyses and Results

### *Main Analyses*

Initially, data was placed in an array that was 2 (age group) by 2 (gender) by 10 (mirror type) by 7 (distance). The first two independent variables were between subjects while the last two were within subjects. The single dependent variable was the glare rating for each subject, each mirror, and each distance. The data were then analyzed by means of an analysis of variance ($\alpha = 0.05$). There were three significant interactions and two significant main effects. Gender was not significant in any interaction or main effect. Age group appeared as interacting significantly with distance in a two way interaction $F(6,96) = 3.1$, $p = 0.0082$ and with distance and mirror type in a three-way interaction $F(54,864) = 1.41$, $p = 0.029$. In addition, the mirror type and distance interaction was significant $F(54,864) = 22.7$, $p < 0.0001$, and there were main effects in both distance $F(6,96) = 93.43$, $p < 0.0001$ and mirror type $F(9,144) = 10.22$, $p < 0.0001$.

*Interactive Effects*

The results are best explained by means of a sequence of plots. The age by distance interaction is plotted in Figure 35, and shows the unanticipated result that the younger drivers rated the glare higher at and beyond 30 ft (9.2 m). This is an unusual result in that older individuals are usually considered to be more affected by glare. More will be said about this later.

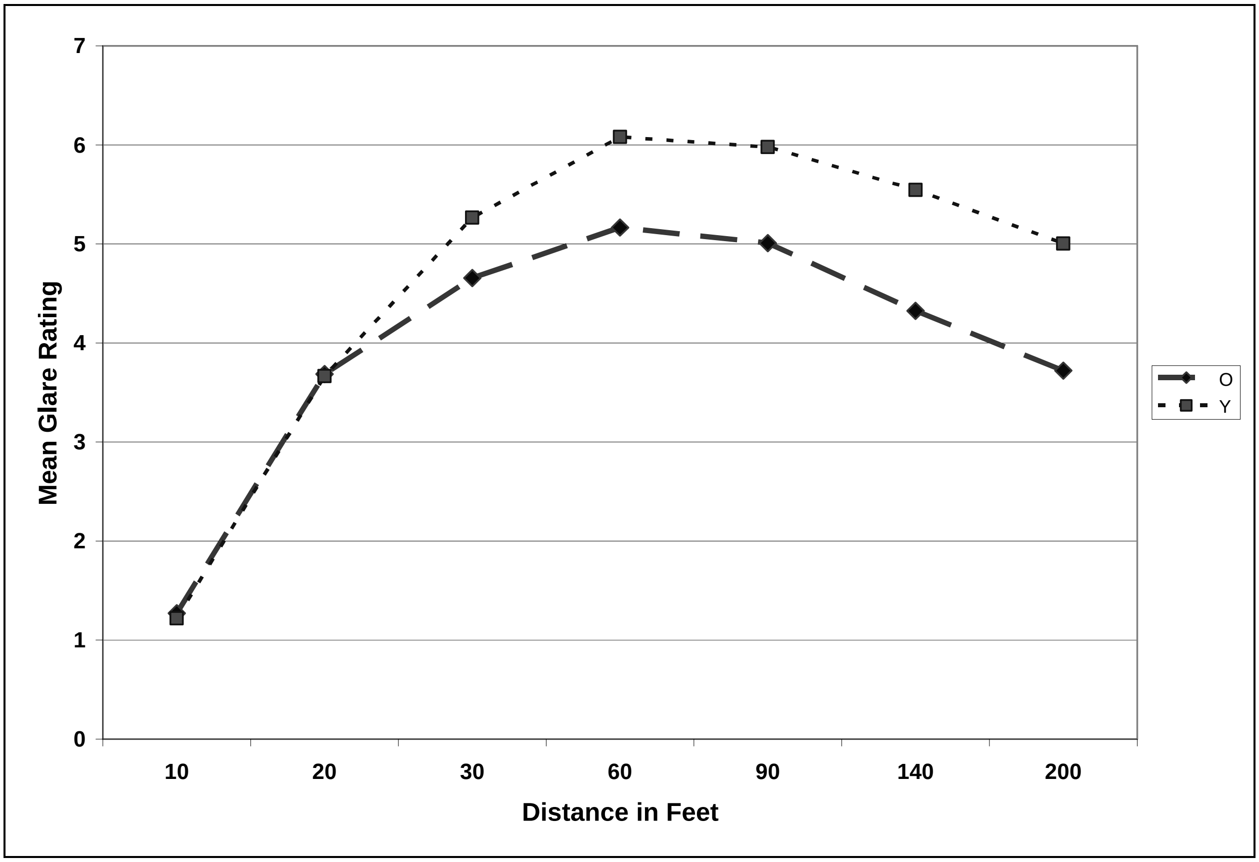


**Figure 35. Plot of the age by distance interaction.**

The three-way interaction is shown by means of two additional plots, one for younger subjects (Figure 36) and one for older subjects (Figure 37). In these plots, the various mirrors are coded as before, however, an additional letter, D or P, is used to distinguish driver-side results for passenger-side results. The results show clearly that the flat mirrors produced the highest ratings, and that these occurred at the longer distances. At the shorter distances, the flat mirror ratings dropped off more quickly, probably as a result of the pickup truck headlights moving out of the field-of-view. The mirrors with the lowest glare ratings were the interior mirror (which was in the nighttime setting) and mirrors with the greater curvature (smaller radius of curvature, that is, 1,400 mm). The two figures show the same trends, but in general, the plots for the younger subjects are a bit higher in rating values for longer distances.

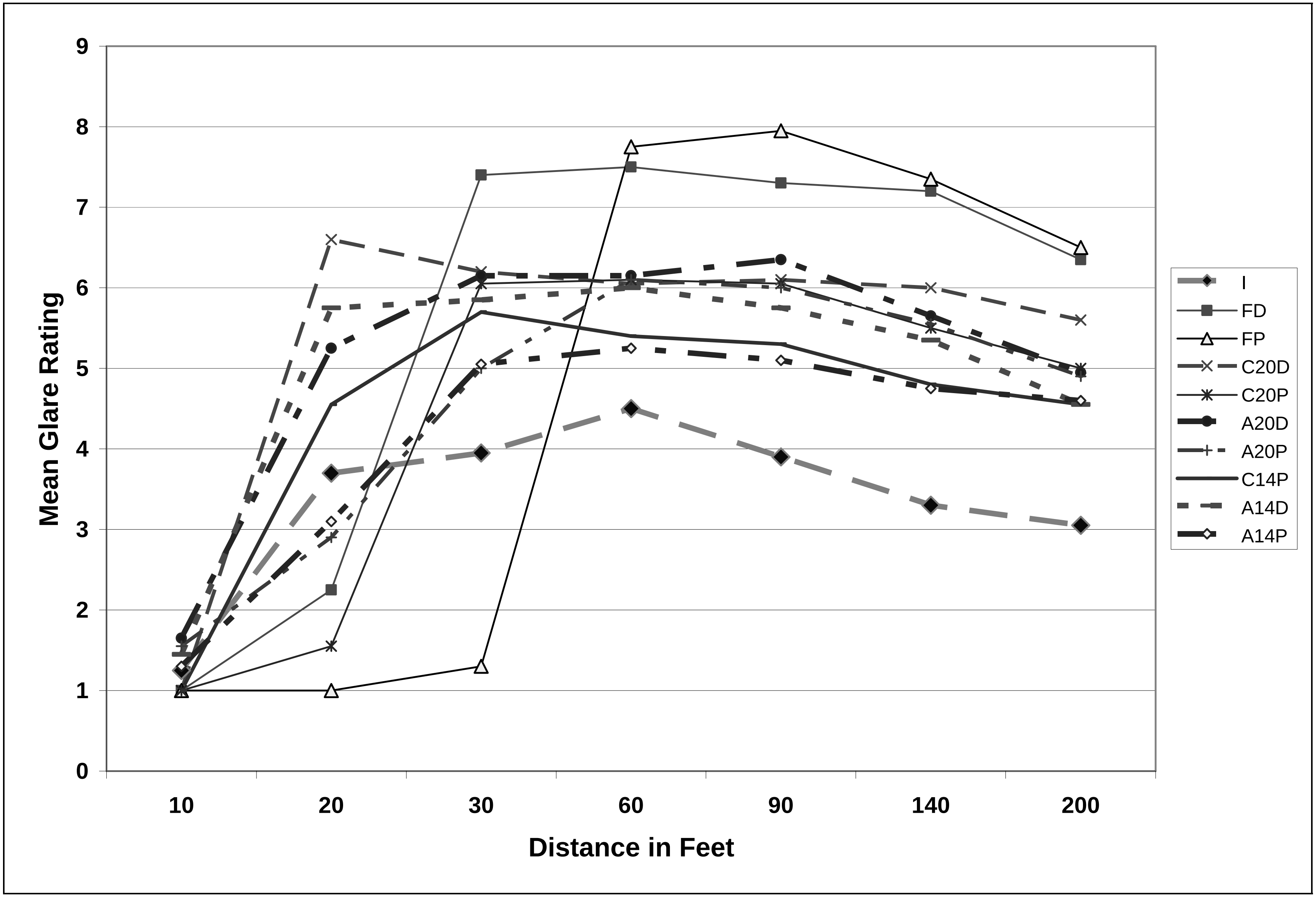


**Figure 36. Plot of mean ratings for the younger subjects as a function of mirror type and distance.**

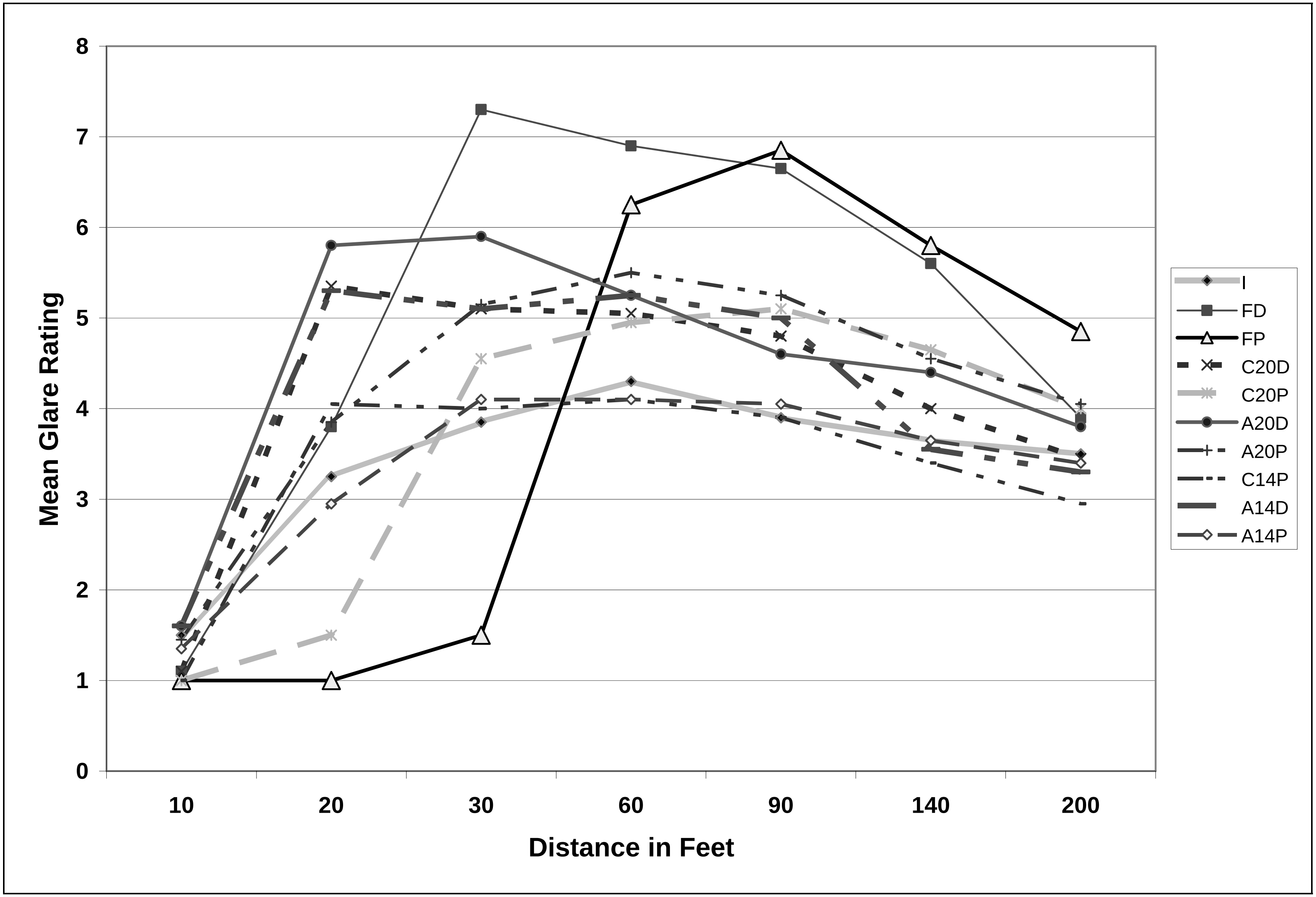


**Figure 37. Plot of mean ratings for the older subjects as a function of mirror type and distance.**

It is important to note in these results that the interior mirror, I, in the nighttime setting produces less discomfort glare than most of the outside mirrors. This finding indicates that several of the outside mirrors are capable of creating much greater glare than the normal setting of the interior mirror.

Recombining the data for the younger and older subjects produces the distance by mirror type interaction, which is plotted in Figure 38. The results exhibit the glare-inducing effects of each mirror as a function of distance. As in Figures 36 and 37, the flat mirrors have the sharpest cut-off and the highest values at the greater distances. Note that the driver-side flat mirror produces high levels of glare all the way in to 30 ft (9.2 m) whereas, because of its narrower field-of-view, the passenger-side flat mirror produces high levels of glare only in to about 60 ft (18.3 m).

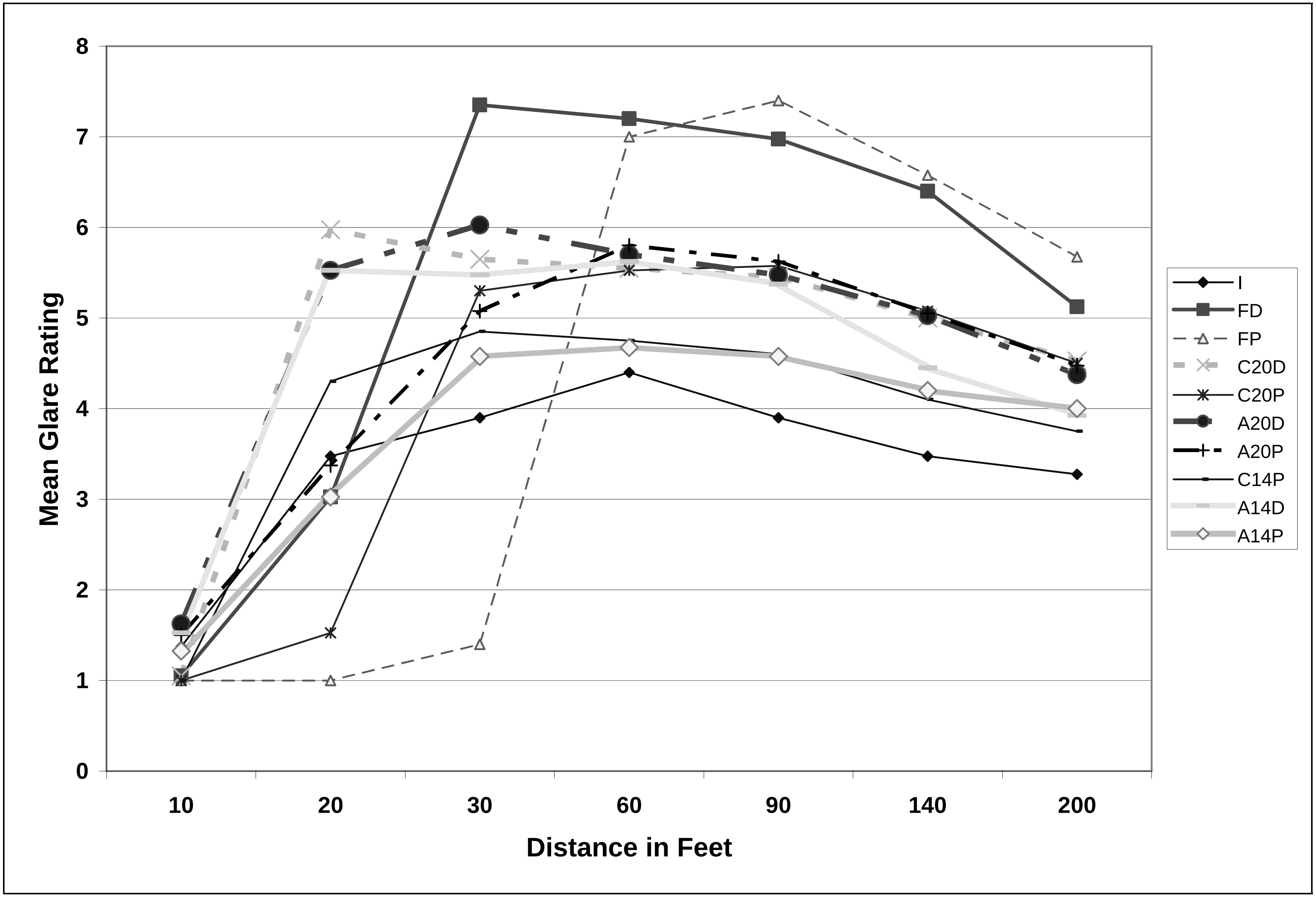


**Figure 38. Plot of the mirror type by distance interaction.**

*Main Effects*

The main effect of mirror type is plotted in Figure 39. Mean values differ significantly only if they do not possess a common letter (at the tops of their respective values, SNK test). As can be seen, overall, the driver-side flat mirror leads the pack in terms of causing glare. It is significantly more glare-producing than all of the other mirrors except A20D and C20D. Similarly, the interior mirror is significantly less glare-producing than all other mirrors except C14P and A14P. More generally, note that the driver-side mirrors tend to have higher mean glare ratings than the passenger-side mirrors and the interior mirror. An important significant effect is the comparison of the flat (FD) and aspheric (A14D, 1,400 mm) mirrors on the driver side. The A14D produces significantly less glare.

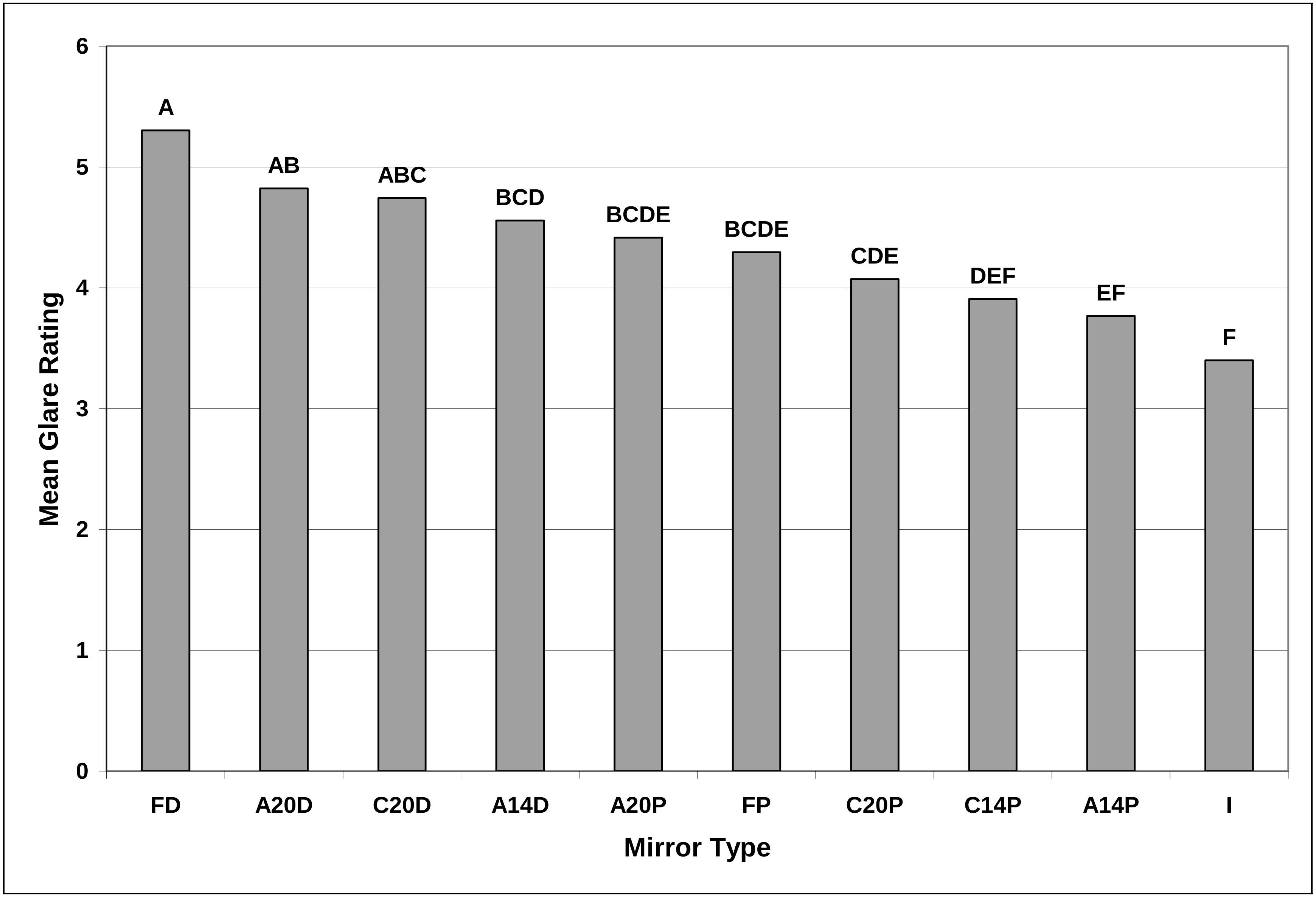


**Figure 39. Plot of the main effect of mirror type on mean glare rating.**
**(Means with a common letter do not differ significantly, $\alpha = 0.05$).**

The main effect of distance is plotted in Figure 40. This figure shows that in general the mirrors produce significantly more glare at distances of 60 to 90 ft (18.3 to 27.4 m) than at all other distances (SNK test). The glare ratings drop off in both directions, with significant steps as a function of distance. Note specifically that at 30 and 140 ft (9.2 and 42.7 m) the mean glare ratings are virtually the same. Outside these distances, the tail-off is significantly more rapid toward short distances than long distances. The reason for this appears to be that the pickup truck lights move outside the main reflection range for the outside mirrors, while for the interior mirror they are partly or completely blocked by the vehicle trunk.

*Time-Related Analyses*

An important question in regard to the experiment is whether there were significant gradual learning and fatigue (time-on-task) effects. As indicated previously, the first two sets of ratings were deleted from the data set and replaced by repeated ratings at the end of the data gathering session. Without checking, it is not clear whether this procedure was adequate in controlling for such effects. Because of counterbalancing, presentation order in time (called "position") could be checked to determine if there were significant order effects.

There were 10 positions in this experiment: 10 mirrors were tested in counterbalanced order. For each position and each subject, the average rating was computed (average across all distances for the given mirror, see Table 14). This resulted in a 2 (age group) by 2 (gender) by 10 (position) data array with position being the sole within-subjects variable. When the data were subjected to an analysis of variance, there were no significant main effects or interactions. In particular, for the position main effect, the result was $F(9,144) = 0.45$, $p = 0.904$. Figure 41 shows the average glare rating as a function of position (that is, time order of presentation). Clearly, there is remarkable uniformity in the average rating values. It appears that gradual learning and fatigue/time-on-task did not have any observable effect on the ratings.

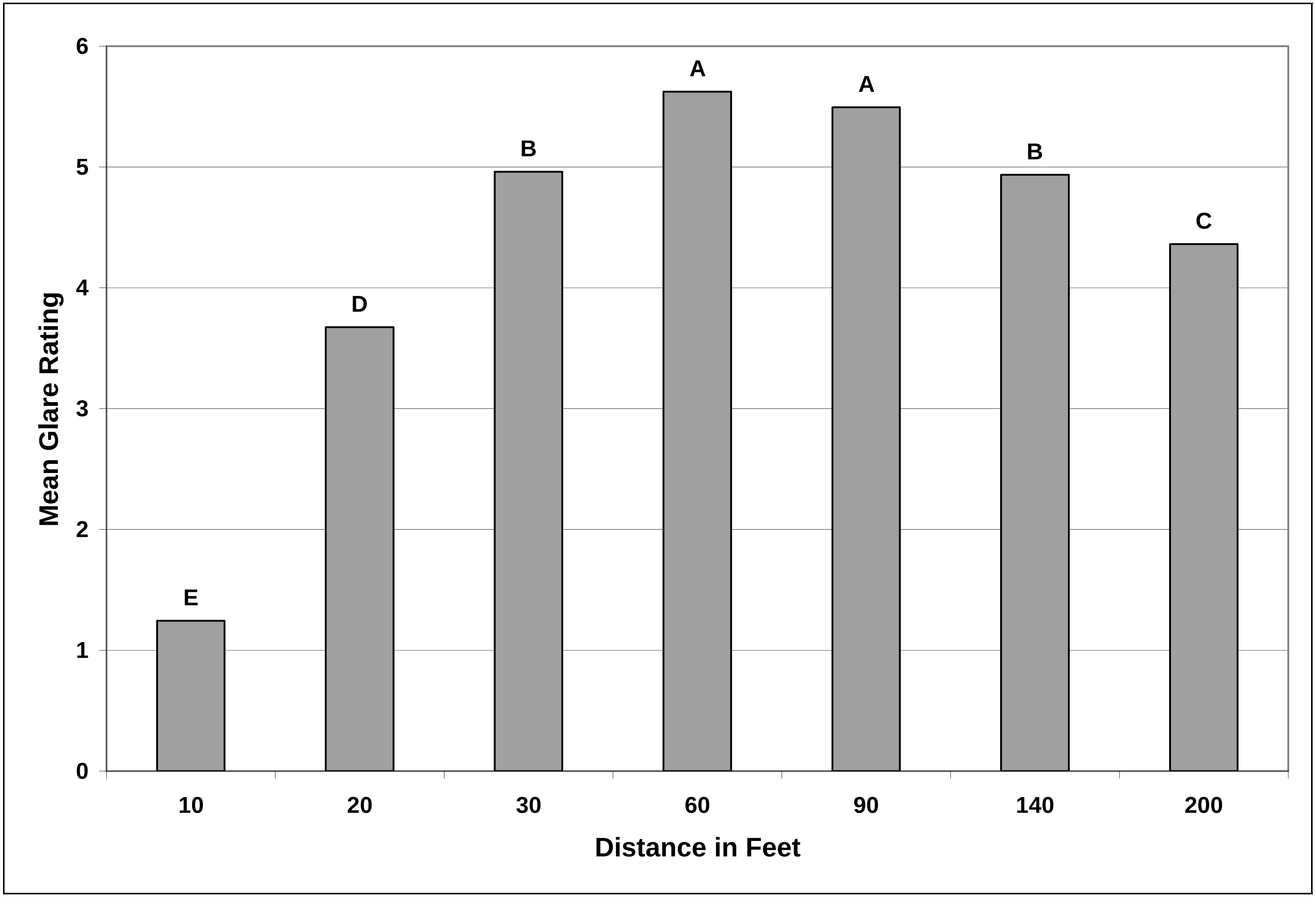


**Figure 40. Plot of the main effect of distance on mean glare rating.**
**(Means with common letter do not differ significantly, α = 0.05).**

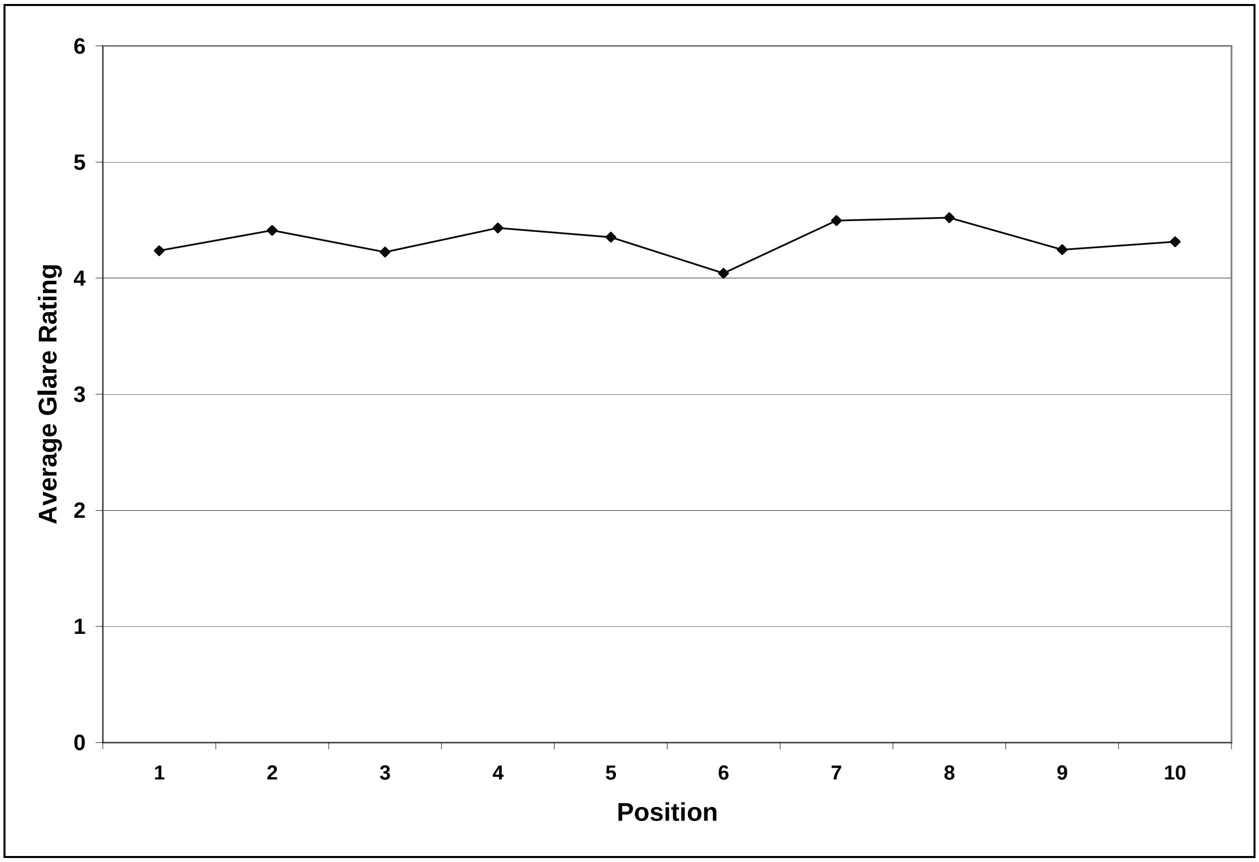


**Figure 41. Average glare rating as a function of position (time order of presentation). (Values are not significantly different from one another.)**

*Additional Analyses Directed Toward Age Effects*

Because of the glare versus age result, additional analyses were carried out to determine if the particular sample of subjects had any performance peculiarities, suggesting an unusual sample. A one-way analysis of variance was performed with subject number (having 20 levels) as the independent variable and rating (having 70 values for each subject) as the dependent variable. The objective was to determine if the distribution of scores as a function of subject number would show any type of outlier effect. Both the distance and type of mirror variables were ignored and all scores for a given subject were treated as being similarly generated.

As expected, the results showed a significant effect of Subject, $F(19,1380) = 15.26$, $p < 0.0001$. The results are plotted in Figure 42. Younger subject mean ratings are shown shaded and older subject mean ratings are shown using a diamond pattern. In addition, post hoc SNK test results are shown; means with a common letter do not differ significantly, $\alpha = 0.05$. The results do exhibit a shift for older subjects, with older subjects 16 and 18 providing significantly lower ratings than all of the younger subjects. At the opposite end, Subject 3 (a younger subject) had a significantly higher rating than all other subjects (which of course includes all older subjects). However, there is substantial overlap in the distributions of average scores, as would be expected due to normal experimental variation.  Thus, there really is very little that would be viewed as unusual.

The data can also be plotted as occurrence data for mean values (Figure 43). The data show similar results with younger subjects distributed toward higher rating values and older subjects distributed toward lower rating values, but with substantial overlap.  All indications are that the results are not heavily influenced by any single subject or pair of subjects, and that the data from each age group appear to have been drawn from a normal distribution.  Consequently, it must be concluded that there are no questionable sources in the data and that the probability is extremely high that the results of the experiment would be repeatable.

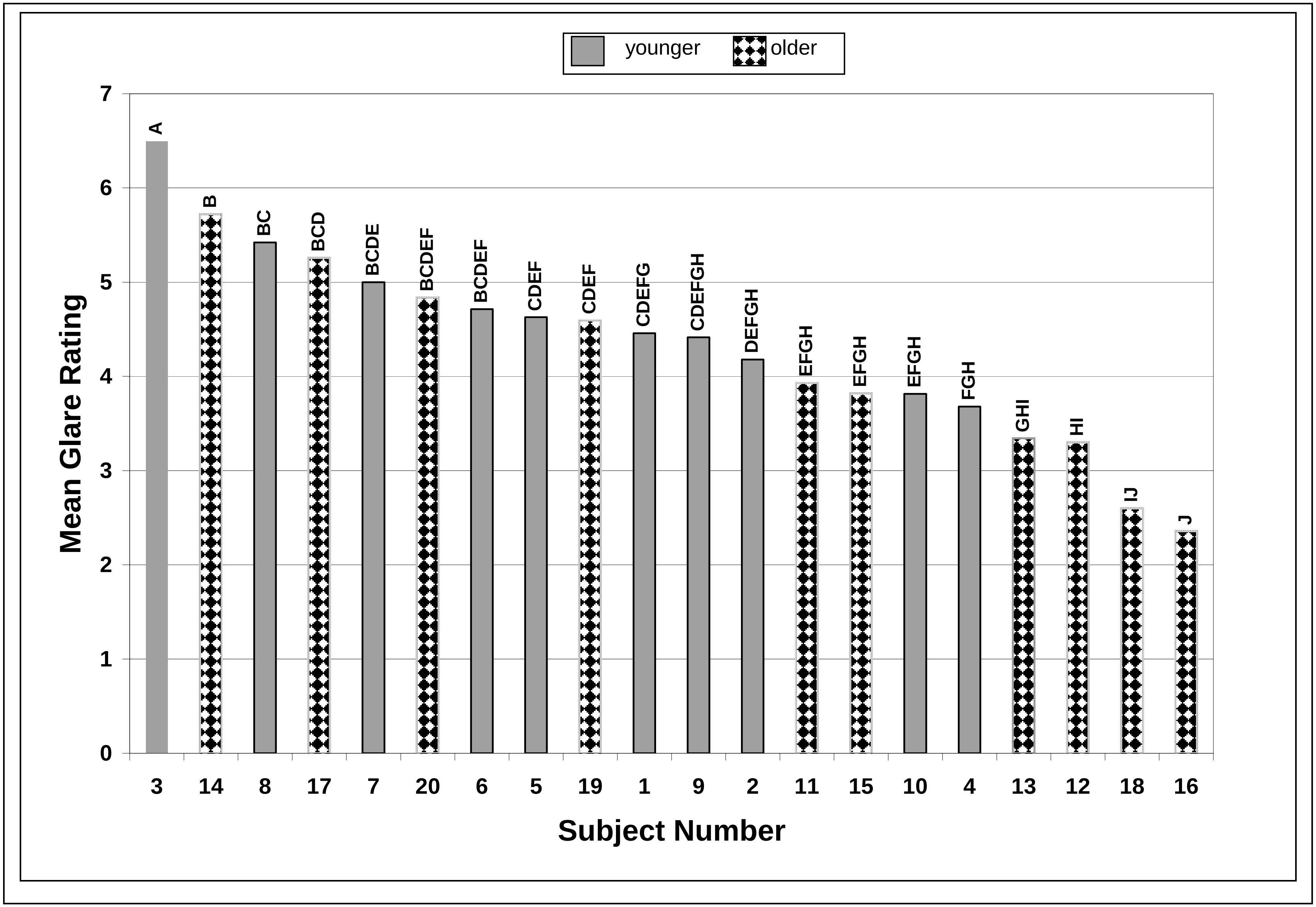


**Figure 42. Mean glare rating as a function of subject number.**
**Means with a common letter do not differ significantly ($\alpha = 0.05$).**

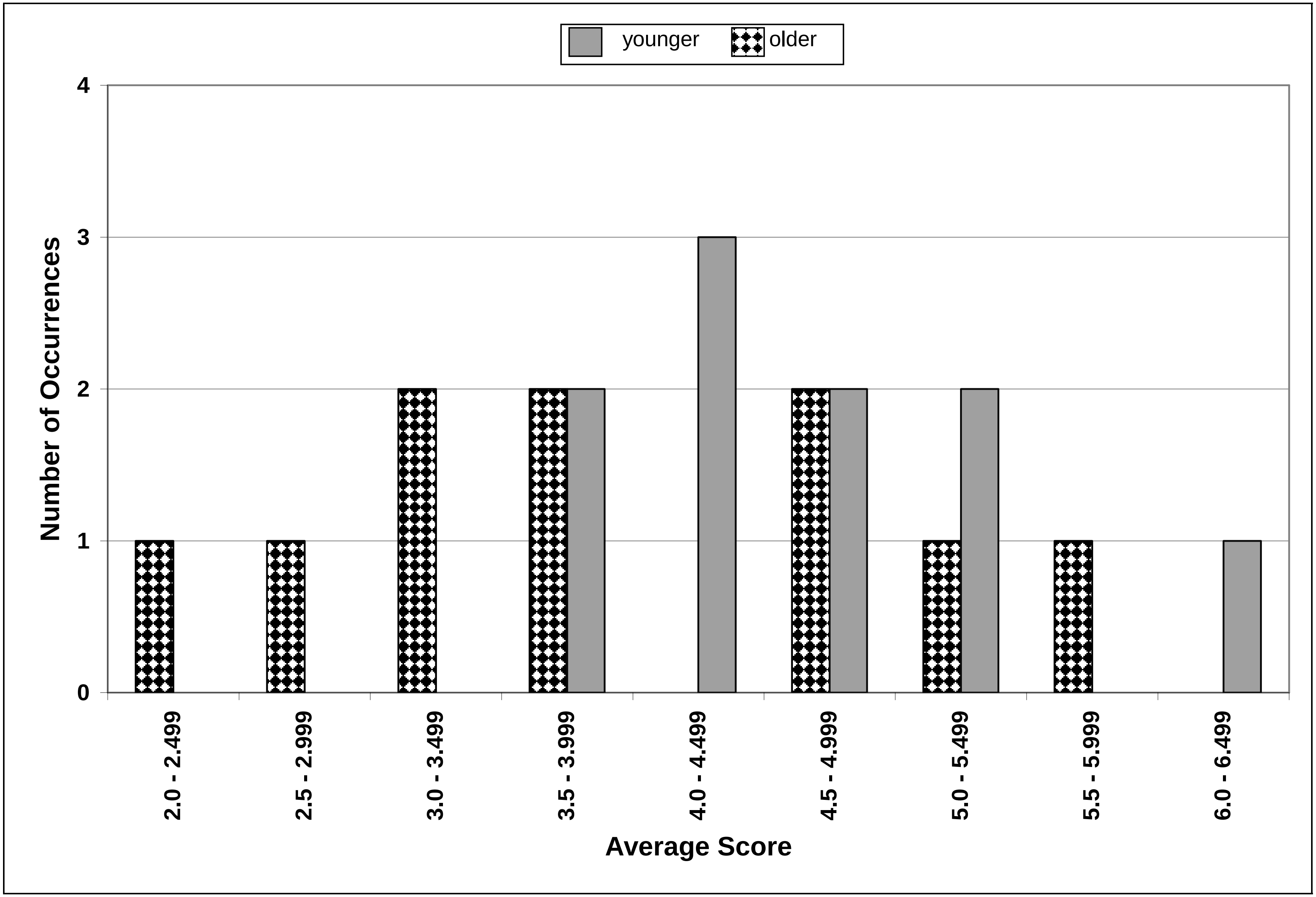


**Figure 43. Distribution of mean glare ratings.**

*Subject Demographics*

Because the glare ratings were higher at longer distances for the younger subjects than for older subjects (Figure 35), a more careful look was taken at the participants. It was hypothesized that vision correction differences might account for this result. In the younger group, five of the subjects wore no vision correction and five did. Of the five who did, all claimed to be nearsighted (myopic). In the older age group, two subjects wore no vision correction, and eight did. Of the eight, six claimed to be nearsighted, one had one nearsighted eye and one farsighted (hyperopic) eye, and one had a complex correction that could not be easily classified.

It appears that the older subject sample may have been somewhat unusual, in that presbyopia frequently involves distance correction for hyperopia. If in fact the subjects were myopic as claimed, then they might have been slightly less susceptible to glare. Correction for myopia involves the use of a divergent (concave) lens. Divergent lenses are known to spread the light entering the patient's eyes, thereby lowering the overall energy density of the light on the retina. This could cause the glare ratings to be slightly lower. There is also the fact that more of the older subjects wore glasses. It could be assumed that the pure transmissivity of the glass or plastic (not including refractive optical properties) would reduce the light entering the eyes by about 10 percent.

Another possible explanation has to do with the vitreous humors and lenses of the older subjects' eyes. It is well known that the vitreous humor yellows and darkens with age, greatly reducing the amount of light reaching the retina. The lens of the eye also has reduced transmissivity (as well as somewhat greater scattering of incoming light). Perhaps the lower level of retinal excitation caused the older drivers to rate the glare somewhat lower.

A final possible explanation is that this glare experiment was somewhat different from most previous experiments. In the usual discomfort glare experiment, the source of the glare is "off-axis" from the task at hand, whereas in this experiment drivers looked directly at the source of the glare (as is appeared in the mirror) just prior to rating it. In such a case, it is possible that the much greater light attenuation within the eye may cause older drivers to rate the glare lower than younger drivers.

There is some precedent for lower discomfort glare ratings for older subjects. Sivak and Olson (1987) found that older subjects actually rated most levels of glare as less discomforting than younger subjects. The authors were developing a methodology for discomfort-glare assessment for oncoming headlamps. They found an age main effect at both low speed (30 mph, 48.3 km/h) and at high speed (60 mph, 96.6 km/h). Older subjects rated the glare to be less on average by about 0.7 of a rating value at low speed and 1.1 of a rating value at high speed, using the conventional (unmodified) deBoer scale. It is important to note that the Sivak and Olson experiment had subjects looking into the glare source, that is, the headlamps. Thus, it is similar to the current experiment in that drivers were instructed to look into the glare source via the mirrors.

## Conclusions

This experiment provides conclusive information regarding how the various types of mirrors induce discomfort glare for the driver. The results are in agreement with predictions that could be made based on the optical analyses and objective experiments performed earlier. On the other hand, age shows significant interactions, with older drivers providing *lower* glare ratings than younger drivers. This means that older drivers are less susceptible to discomfort glare when looking directly into outside mirrors than are younger drivers.

The results of the experiment show that, since glare is essentially a function of mirror curvature (assuming mirror surface reflectances are similar), films and other coatings may be necessary to equalize (lower) glare when different types of mirrors are used. For example, if a flat mirror is used on the driver side and a convex mirror is used on the passenger side, as is currently the convention in the United States, then a coating on the driver-side mirror would be desirable to lower its propensity to cause glare. Of course, the assumption being made is that there are no detrimental (daytime) effects associated with adding the coating.

## PART IV: DYNAMIC (ON-ROAD) TESTING

The previous three parts of this report provide a summary of information on aspheric mirrors, along with comparisons with flat and convex mirrors. Having completed them, it is important to indicate what tests remain to be performed.

Dynamic testing (i.e., testing in moving vehicles in realistic situations) is needed to obtain a more comprehensive picture of the abilities and limitations of aspheric mirrors, as compared with flat and convex mirrors. This form of testing can take two forms: short-term performance and opinion testing, and long-term (longitudinal) performance and opinion testing. The following chapters of this report describe short-term road testing intended to answer the most important remaining questions. Longitudinal testing should be considered for future research, since there may be gradual shifts in performance and opinion as drivers obtain more experience with new types of mirrors.

The short term tests to be described make use of substantial repetition to ameliorate the gradual effects, particularly with regard to performance. The concept is that repetition should help account for initial learning. In addition, comparison testing is used throughout which helps to level the playing field. Chapter 18 describes the experimental design, and Chapter 19 provides the analyses, results, and conclusions.

# CHAPTER 18. DYNAMIC ROAD TEST PLAN COMPARING ASPHERIC AND OTHER TYPES OF REAR-VIEW MIRRORS

## Objectives

This chapter describes tests that were performed on the Virginia Smart Road in Blacksburg, Virginia. The Smart Road is located at VTTI. The road tests followed a good deal of previous research, done both at VTTI and earlier at other institutions. Previous work has been summarized in earlier chapters of this report and also in a previous report (Wierwille, Spaulding, & Hanowski, 2005). The earlier chapters have included information retrieval; optical and mathematical derivations; and static experiments involving flat, convex, and aspheric mirrors. These chapters are relatively comprehensive and indicate that, in general, aspheric mirrors show promise. The dynamic tests, that is, tests in moving vehicles, using aspheric outside rear-view mirrors as well as a variety of comparison mirrors had the objectives of determining driver performance and driver opinion/acceptance in passing and merging.

It is important to understand that many aspects of aspheric mirrors have already been tested, and that it was considered necessary to test only those aspects where additional testing could be helpful. Previous results indicated that aspheric mirrors should provide better detection capability (that is, better detection of other vehicles with which the driver's vehicle might come into conflict) because these mirrors have a wider field-of-view than conventional mirrors, particularly flat mirrors. However, this greater detection capability comes at a potential cost. Aspheric mirrors minify the image of an object appearing in them, and there is also some "squeeze" distortion if the object appears in the outer (aspheric) portion of the mirror. American drivers are already familiar with minification because convex mirrors are commonly used on the passenger side of light vehicles and these mirrors produce minification. However, American drivers are not familiar with the distortion created by aspherics, and they are not used to any mirror other than flat on the driver side of the vehicle. Thus, it was considered important to obtain information on whether they find alternative mirrors acceptable and can use them effectively in safety critical situations.

The only previous research information available on acceptance is that reported by Flannagan and Flannagan (1998), in which employees of the Ford Motor Company were provided with a variety of different driver-side mirrors, some of which were aspherics. The results suggested that aspheric mirrors would generally be accepted and that acceptance would increase over time. However, the subjects in this case would be considered substantially better informed on automotive-related technology than the general motoring public. The only other indication of acceptance is that provided by the general fact that the mirrors are used in the European Union without known documentation of driver complaint. While these findings suggest acceptance, they do not positively demonstrate it. Consequently, one of the objectives of the dynamic tests was to determine the degree of driver acceptance, particularly when compared side by side with flat and convex mirrors as well as some newer alternatives that will be described.

Driver opinion and driver acceptance can be difficult to assess, because they are often dependent on the amount of time and practice the driver has spent with the new alternative. Unfamiliarity and the initial adaptation process can potentially lower driver opinion and hinder acceptance. The current experiment was set up to minimize to the extent possible these initial adaptation effects. However, because the study did *not* involve several weeks or months of data taking, it has the limitation of not being capable of providing information on the long-term trends that might take place in driver opinion and acceptance. Clearly, a separate field study using multiple vehicles would be needed to definitively answer questions of opinion associated with long-term exposure. The Flannagan and Flannagan (1998) study provides some long-term information, but is not definitive because the subject population was clearly not representative of the general driving public in the United States.

Also, in determining driver acceptance, it is important to realize that drivers generally use combinations of mirrors and possibly direct looks to perform various maneuvers. For example, in merging or re-merging to the right, the driver is likely to use the passenger-side mirror, the interior rear-view mirror, and possibly, direct looks to the right rear. So, in obtaining driver opinion with regard to aspherics, it was deemed important to obtain ratings and performance data regarding the combination of mirrors and direct looks.

In regard to aspherics, it appears that the largest *potential* shortcoming has to do with gap acceptance. If gap acceptance is substantially reduced with these mirrors, then it is possible that they could increase the crash rate. The logic here is that reduced gap size might occasionally result in a crash because of inadequate clearance. On the other hand, since gap acceptance is the most likely shortcoming, if that shortcoming is small or nonexistent, the mirrors can be considered to be no riskier than presently used mirrors. While such an argument does not provide support for aspherics, other aspects, such as greater fields of view for aspherics, then suggest that object detection is better (see Helmers et al., 1992).

The only known previous work on gap acceptance in relation to aspherics is that performed by de Vos (2000) and de Vos, Van der Horst, and Perel (2001) using Dutch drivers. In a relatively comprehensive test track experiment, they showed that gaps were somewhat smaller for both spherical (convex) mirrors and for aspheric mirrors when used on the driver side. Using a technique called the "last safe gap," they showed that gap time was reduced by about 0.5 s for both an aspheric and a convex mirror having a 1,400 mm radius of curvature in the convex portion, and reduced by about 0.3 s for an aspheric having a 2,000 mm radius of curvature in its convex portion (see Figure 31 in de Vos, 2000). These represent 11.7 percent and 7.0 percent reductions, respectively. While small, the reductions were statistically reliable.

There are two important considerations in regard to de Vos, Van der Horst, and Perel study. First, the study was performed with the interior mirror turned down so it could not be used. Thus, the drivers were only able to use the outside mirror (presumably combined with direct looks). In the investigators' words, the study represented a "worst case" situation. It would seem that gap acceptance should also be tested under the more usual circumstance in which the driver uses a combination of interior and outside rear-view mirrors. The other consideration is in regard the closing rates used: 20 km/h (12.4 mph) and 50 km/r (31.1mph). These rates are believed to be above those normally encountered in traffic, particularly the 50 km/h (31.1 mph) closing speed. For example, at a speed of 60 mph (96.6 km/h), the speed of the vehicle coming from behind would be over 90 mph (144.8 km/h). While such encounters do occur, they are extremely rare. Normal closing rates are believed to be in the range of 8 to10 mph (12.9 to 16.1 km/h).

Thus, the Smart Road experiments 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 side or the passenger side, both sides were examined. (There has been very little dynamic testing done on passenger-side aspherics.)

### Mirrors Included in the Experiment

Mirrors included in the road tests were chosen on the basis of several factors. Of course, the mirror complement included aspherics that are typical candidates, so that they could be evaluated. In addition, other types of mirrors were included for comparison purposes. These mirrors included what might be considered baseline mirrors, and as well as possible competing alternatives. Driver-side mirrors were considered separately from the passenger side. There were 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 et al., 2005; see also Figure 6, Chapter 7 and Figure 18, Chapter 14 of the current report). 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-side and passenger-side mirrors. Consequently, mirrors selected as baselines differed for the two sides of the vehicle.

#### *Driver-Side Mirrors Tested*

Current U.S. regulations require a flat (planar) mirror on the driver side of the vehicle. Researchers have concentrated on this side in the belief that alternative mirrors might be preferable. In particular, it is believed by some researchers 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. Chapter 14 of this report shows that, indeed, a typical flat mirror results in a huge blind spot when aimed as drivers typically aim their mirrors. In any case, since a flat mirror is currently required by the regulations, the F-D (flat, driver-side) mirror 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 2,000 mm, producing mild minification and almost twice the field-of-view of approximately 22.6 deg (Table 7 of Chapter 14). 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 deg (Table 7 of Chapter 14) 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 (Table 7, Chapter 14), but less minification than the A14-D. Both mirrors represent viable alternatives with large fields of view (Figures 22 and 23, Chapter 14).

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, & 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 rear-view-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 1,400 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. Figure 44 shows the F-Elongated-D mounted on the vehicle. Because the mirrors were relatively large, they were offset from the mirror frame by light-weight spacers. The angular position of the mirrors could then be controlled from inside the vehicle in the usual manner. The spacer was trimmed so that it did not conflict with the edges of the mirror frame. 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 (with spacers) 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.

**Figure 44. The F-Elongated-D mirror mounted on the driver's side of the vehicle.**

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. The seven mirrors are shown in the photograph of Figure 45. Each mirror's characteristics are summarized in Table 15.

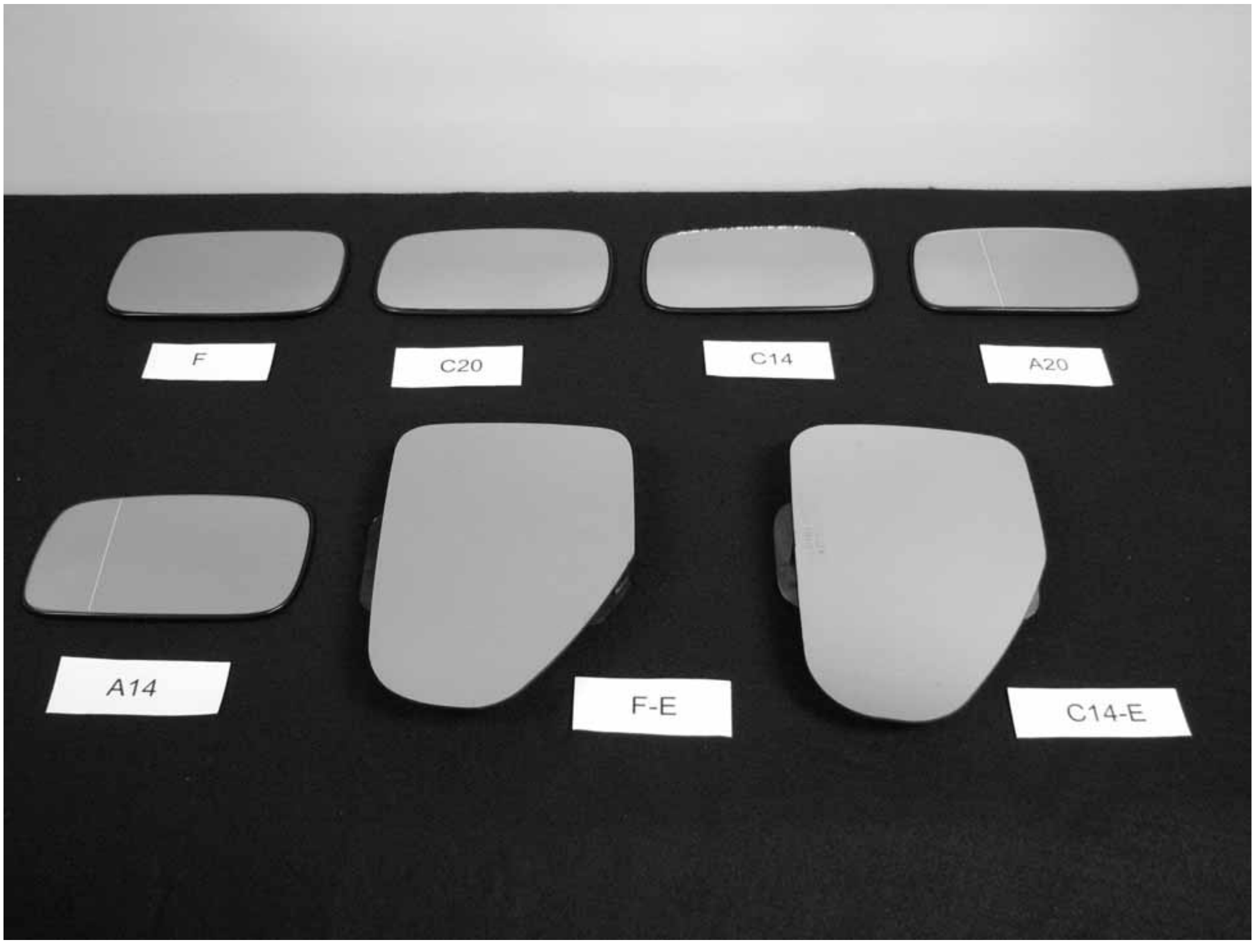


**Figure 45. The seven mirrors used for the driver-side tests.**

**Table 15. Summary of characteristics of mirrors used on the driver side in the Smart Road experiments.**

| | |
|---|---|
| **1) Flat (Planar).**<br>Designation: **F-D**<br>Reason for Inclusion: Baseline (same as mirrors currently used on the driver side in the U.S.).<br>Advantages: Unit magnification. No image distortion.<br>Disadvantages: Narrow field-of-view. High nighttime glare. | **5) Aspheric, 1,400 mm radius of curvature in convex portion.**<br>Designation: **A14-D**<br>Reason for Inclusion: Aspheric believed to possess reasonably good features.<br>Advantages: Excellent angular coverage. Reduced nighttime glare under most circumstances.<br>Disadvantages: High level of minification in the convex region. Image distortion (objects squeezed) in the aspheric region. |
| **2) Convex, 2,000 mm radius of curvature.**<br>Designation: **C20-D**<br>Reason for Inclusion: Alternative to an aspheric, with moderate field-of-view.<br>Advantages: Mild minification with no other image distortion. Reduced nighttime glare.<br>Disadvantage: Field-of-view, although wider, may not be adequate. | **6) Flat-Elongated**<br>Designation: **F-Elongated-D**<br>Reason for Inclusion: Potential for better distance estimation by driver.<br>Advantages: Unit magnification. No image distortion. Some degree of foreground viewable.<br>Disadvantages: Narrow horizontal field-of-view. High nighttime glare. |
| **3) Convex, 1,400 mm radius of curvature**<br>Designation: **C14-D**<br>Reason for Inclusion: Alternative to an aspheric, with better field-of-view.<br>Advantages: Moderate angular coverage. No distortion other than minification. Substantially reduced nighttime glare.<br>Disadvantages: Field-of-view may not be adequate. High level of minification. | **7) Convex, 1,400 mm radius of curvature, Elongated.**<br>Designation: **C14-Elongated-D**<br>Reason for Inclusion: Alternative to an aspheric, with better field-of-view than a flat mirror and potential for better distance estimation.<br>Advantages: Moderate horizontal angular coverage. No distortion other than minification. Substantially reduced nighttime glare. Some degree of foreground viewable.<br>Disadvantages: Field-of-view may not be adequate. High level of minification. |
| **4) Aspheric, 2,000 mm radius of curvature in convex portion.**<br>Designation: **A20-D**<br>Reason for Inclusion: Aspheric believed to possess the best combination of features for the driver side.<br>Advantages: Excellent angular coverage, mild minification in the convex portion. Reduced nighttime glare under most circumstances.<br>Disadvantage: Image distortion (objects squeezed) in the aspheric portion. | |

### *Passenger-side Mirrors Tested*

The situation on the passenger side differs, as previously explained. Current regulations allow for a flat or a convex mirror to be used on the passenger side. However, industry practice has been to provide convex mirrors on the passenger side of new light vehicles. Consequently, there are no known new light vehicles with flat mirrors on the passenger side. The regulations require that if a convex mirror is used, it must have a radius of curvature between 889 and 1,651 mm. A brief examination of 60 light vehicles in a typical parking lot showed that the mirrors had radii of curvature between 970 to 1,460 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 1,400 mm radius of curvature falls within the range actually used on vehicles. The mirror produces a one-eyed field-of-view of approximately 21 deg with good nighttime glare attenuation, but with substantial image minification (Table 8, Chapter 15).

As shown in Chapter 15, many vehicles currently have convex mirrors with radii of curvature around 1,000 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 1,000 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.

Note that a C20-P was not included on the passenger side for testing. The reason for this is that it does not have the necessary field-of-view when used on the passenger side, and it also falls outside current U.S. regulations. Since drivers now use mirrors with radii of curvature between 889 and 1,651 mm and the corresponding fields of view created by them, it seemed undesirable and unnecessary to test such a mirror, which has less curvature. Similarly, since flat mirrors are no longer used on the passenger side of light vehicles, and since they have a very narrow field-of-view, they were not considered to be viable candidates for modern light vehicles.

There were two possible alternative aspheric mirrors for the passenger side, the A14-P and the A20-P. Both mirrors provide a one-eyed field-of-view of at least 35 deg, and both provide substantial glare reduction in nighttime driving (Table 8, Chapter 15). The A14-P mirror has a convex portion with a radius of curvature of 1,400 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 that have been sold in the United States It meets the U.S. regulations by providing a convex portion meeting the regulations.

The A20-P has less curvature in its convex portion, that is, 2,000 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.

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.
Figure 46 shows the C14-Elongated-P mounted on the passenger side of the vehicle.

**Figure 46. The C14-Elongated-P mirror mounted on the passenger side of the vehicle.**

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. The five mirrors are shown in the photograph of Figure 47. The characteristics are summarized in Table 16.

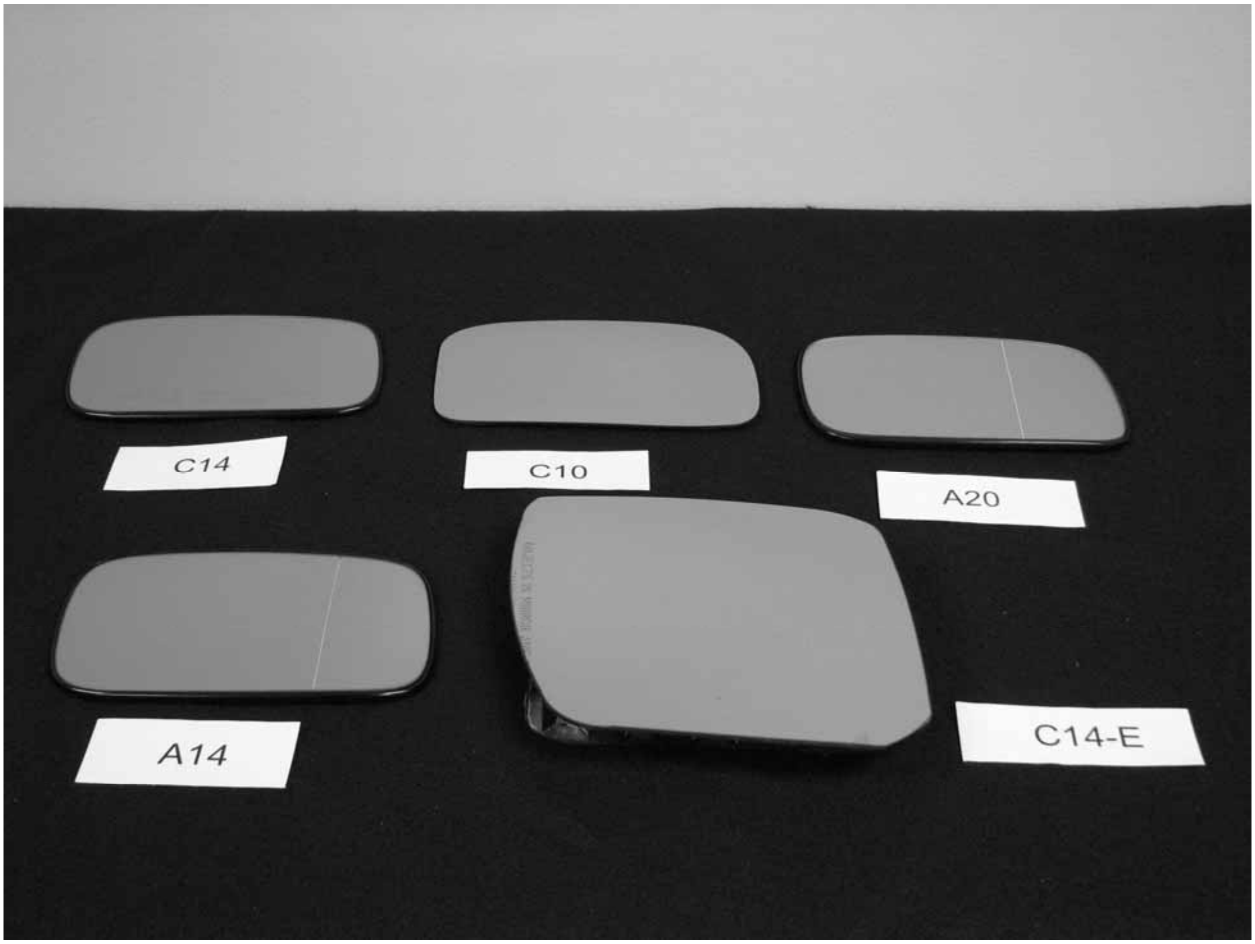


**Figure 47. Five mirrors used for the passenger-side tests.**

**Table 16. Summary of characteristics of mirrors used on the passenger side in the Smart Road experiments.**

| | |
|---|---|
| **1) Convex, 1,400 mm radius of curvature.**<br><br>Designation: **C14-P**<br>Reason for Inclusion: Baseline (similar to mirrors currently used on the passenger side in the U.S.).<br>Advantages: Moderate angular coverage. No distortion other than minification. Substantially reduced nighttime glare.<br>Disadvantages: Field-of-view may not be adequate. High level of minification. | **4) Aspheric, 1,400 mm radius of curvature in convex portion.**<br><br>Designation: **A14-P**<br>Reason for Inclusion: Aspheric believed to possess the best combination of features for the passenger side.<br>Advantages: Excellent angular coverage, with the same image minification (as the baseline) in the convex portion. Substantially reduced nighttime glare.<br>Disadvantages: Image distortion (objects squeezed) in the aspheric portion. High level of minification in the convex portion. |
| **2) Convex, 1000 mm radius of curvature.**<br><br>Designation: **C10-P**<br>Reason for Inclusion: Alternative baseline (similar to mirrors currently used on the passenger side of some U.S. vehicles).<br>Advantages: Reasonably good coverage. No distortion other than minification. Substantially reduced nighttime glare.<br>Disadvantages: Field-of-view may be only barely adequate. Very high level of minification. | **5) Convex, 1,400 mm radius of curvature, Elongated.**<br><br>Designation: **C14-Elongated-P**<br>Reason for Inclusion: Potential for better distance estimation by driver.<br>Advantages: Moderate angular coverage. No distortion other than minification. Substantially reduced nighttime glare. Some degree of foreground viewable.<br>Disadvantages: Horizontal field-of-view may not be adequate. High level of minification. |
| **3) Aspheric, 2,000 mm radius of curvature in convex portion.**<br><br>Designation: **A20-P**<br>Reason for Inclusion: Alternative aspheric with less minification in the convex portion.<br>Advantages: Excellent angular coverage, but with less image minification in the convex portion. Reduced nighttime glare.<br>Disadvantages: Image distortion (objects squeezed) in the aspheric portion. Aspheric portion is slightly wider. | |

## Experimental Scenario

### *Smart Road*

The experiment was run on the Smart Road, a research facility at VTTI with controlled access. The Smart Road is fundamentally a two-lane road built to interstate standards with substantial instrumentation. It is 2.1 miles (3.4 km) long (each direction), with a large turnaround at the near end and a moderate-size turnaround at the far end. Access to the road is controlled from a control room (dispatch). This room maintains video surveillance at all times. Radio communications exist among all vehicles on the road and dispatch.

The Smart Road has the capability of determining distances between equipped vehicles using a differential global positioning system (DGPS). This system, which relies on a local reference transmitter and the global positioning system (GPS), allows measurements between vehicles accurate to approximately 3 cm (1.2 in). Consequently, it was used for measurements of distance between vehicles on the Smart Road.

*Scenario for Each Outside Rear-View Mirror*

Each mirror was evaluated using two full loops (four legs, two outbound and two inbound) of the Smart Road. All outbound legs were run in an identical manner and all inbound legs were run in an identical manner. Outbound legs involved passing and merging, while inbound legs involved determination of last comfortable gap," which will be explained later. The scenarios used two confederate vehicles and the subject vehicle. The drivers of the confederate vehicles and the lead experimenter in the subject vehicle coordinated the scenario by means of two-way radio.

During the outbound leg one passing maneuver and two merging maneuvers were performed by the driver. Figure 48 depicts the passing maneuver for the driver-side mirrors, and Figure 49 depicts it for the passenger-side mirrors. Note that these figures and those that follow showing the maneuvers are not to scale. 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 confederate vehicles were traveling at 30 mph (48.3 km/h) at the time of the pass. The maneuver was intended to provide a realistic passing scenario in which the mirrors would most likely be used. The first merging (as opposed to passing) scenario is depicted in Figures 50 and 51 for the driver-side and passenger-side rear-view mirrors, respectively. Basically, 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). The second merging scenario is depicted in Figures 52 and 53, again for the driver-side and passenger-side rear-view mirrors, respectively. In this case, 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.

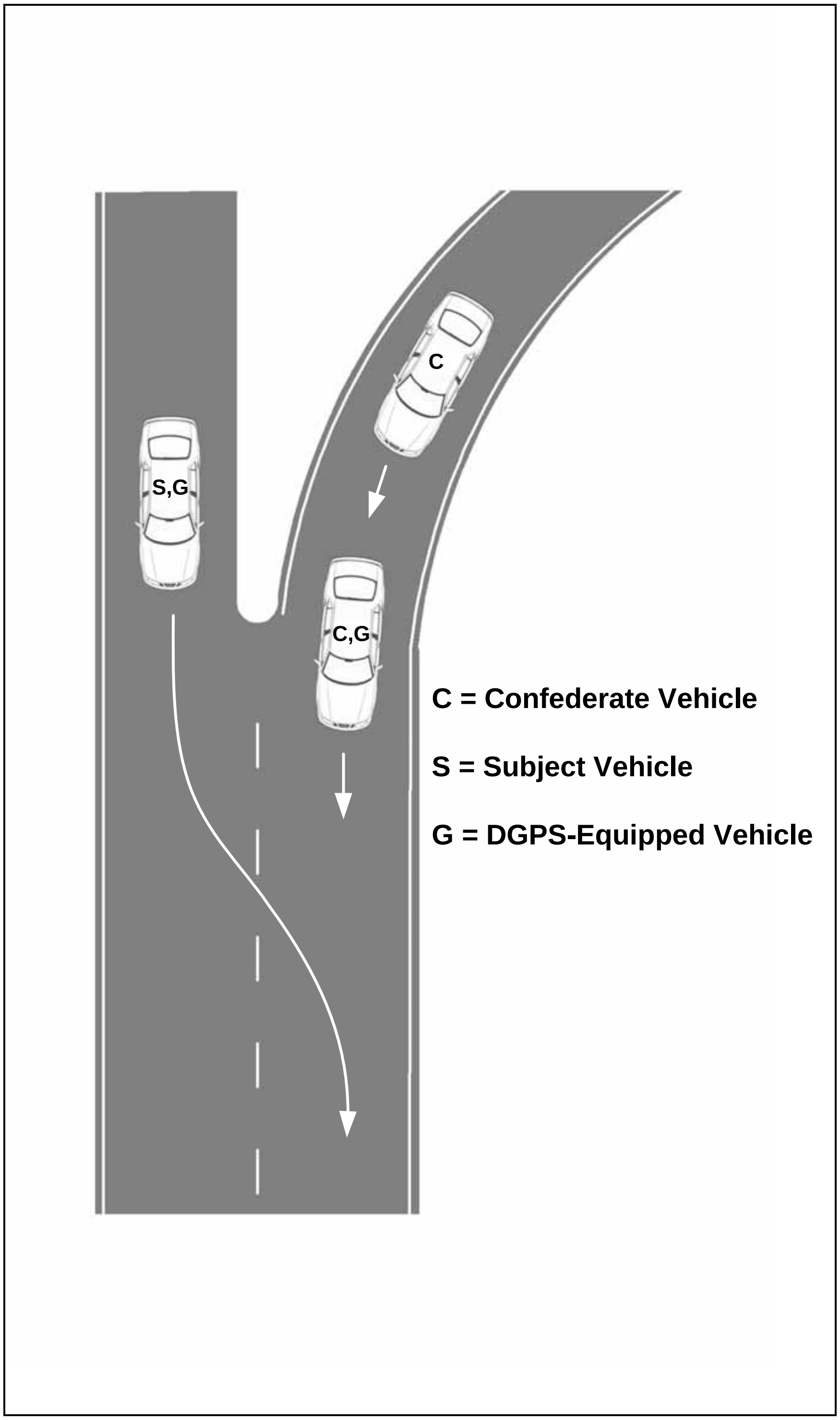


**Figure 48. Passing maneuver; confederates initially alongside subject. Driver-side mirror test. (Distances are not to scale.)**

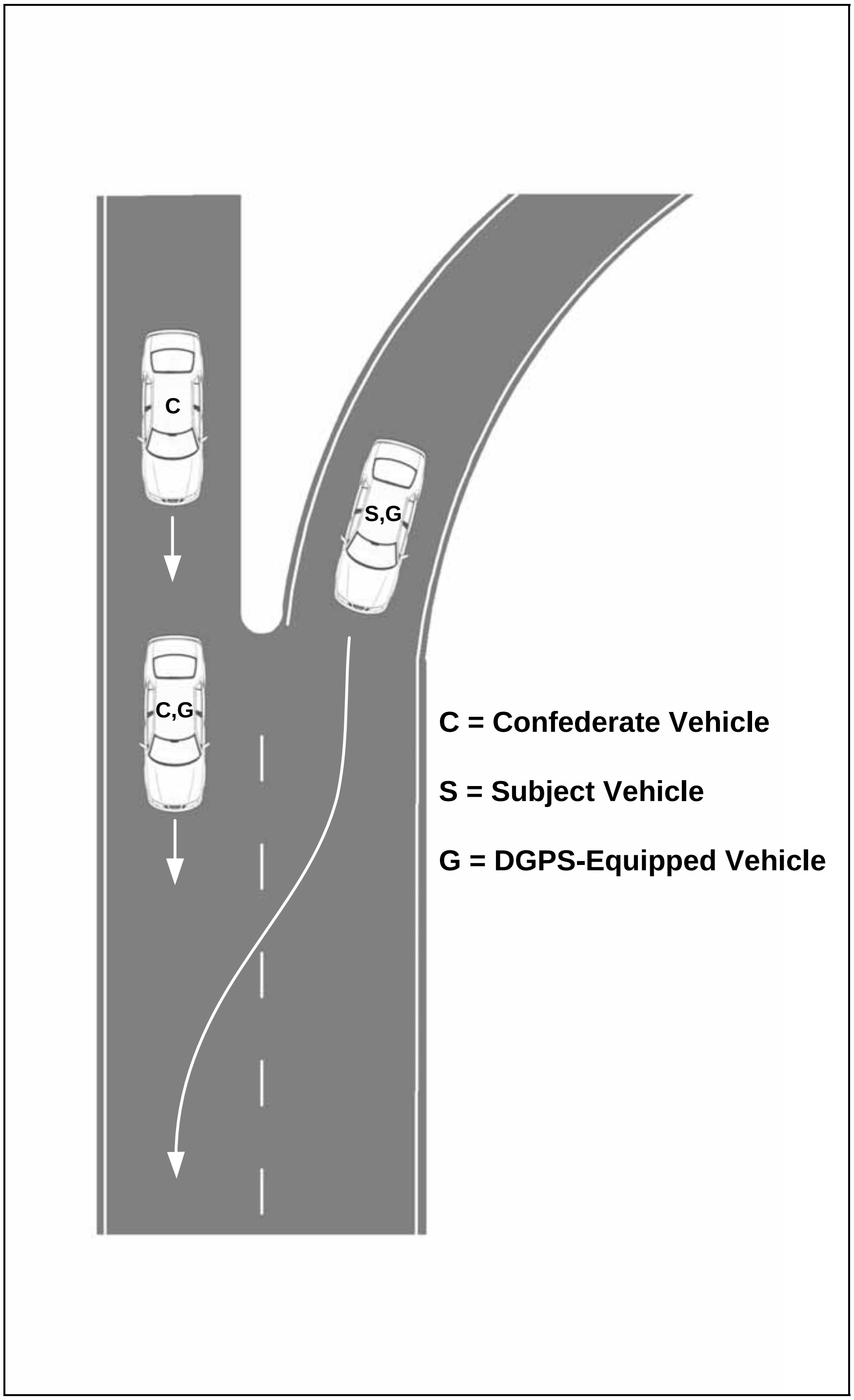


**Figure 49. Passing maneuver; confederates initially alongside subject. Passenger-side mirror test.**
**(Distances are not to scale.)**

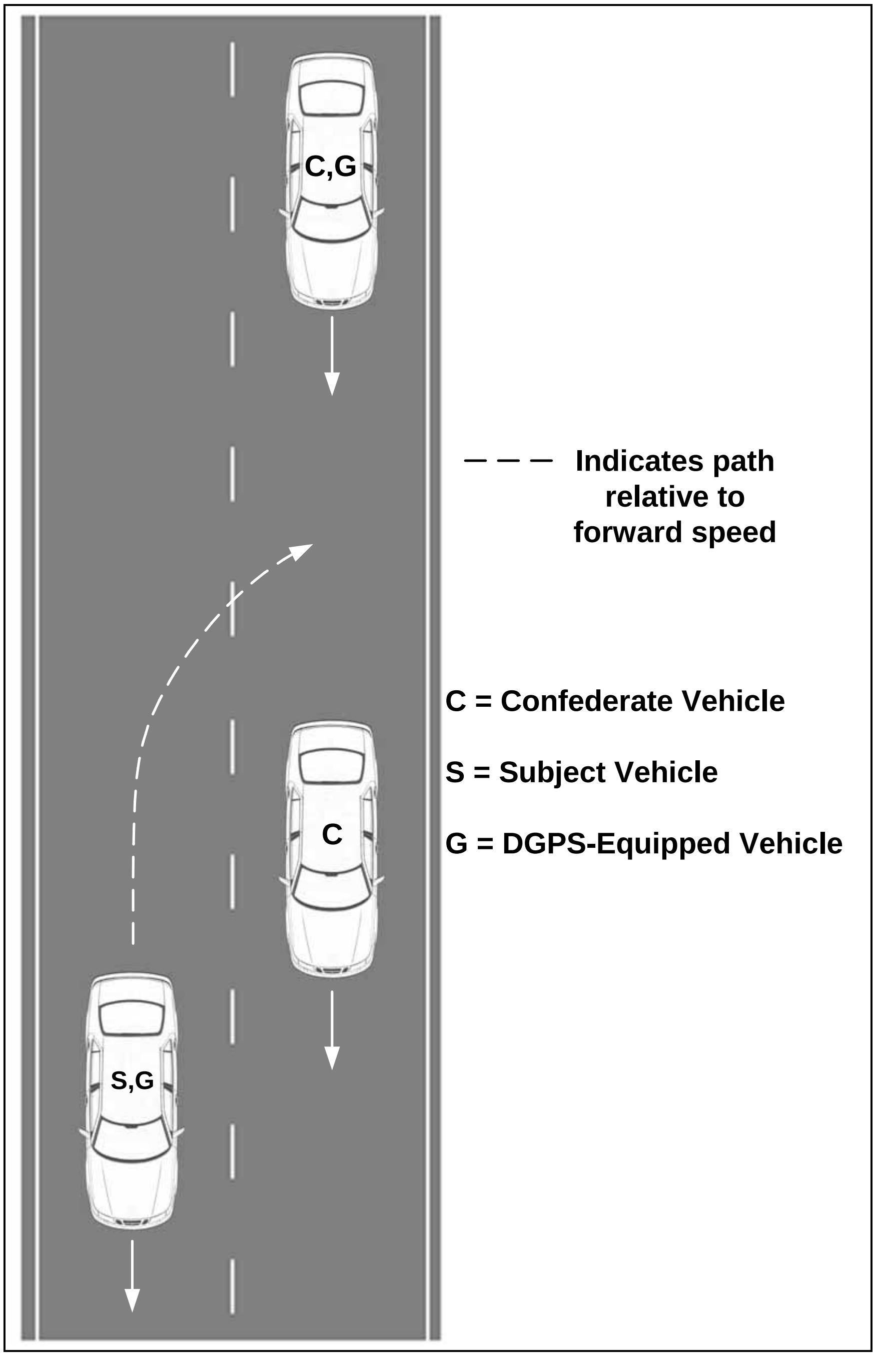


**Figure 50. Decelerating merge maneuver; confederates initially behind the subject. Driver-side mirror test. (Distances are not to scale.)**

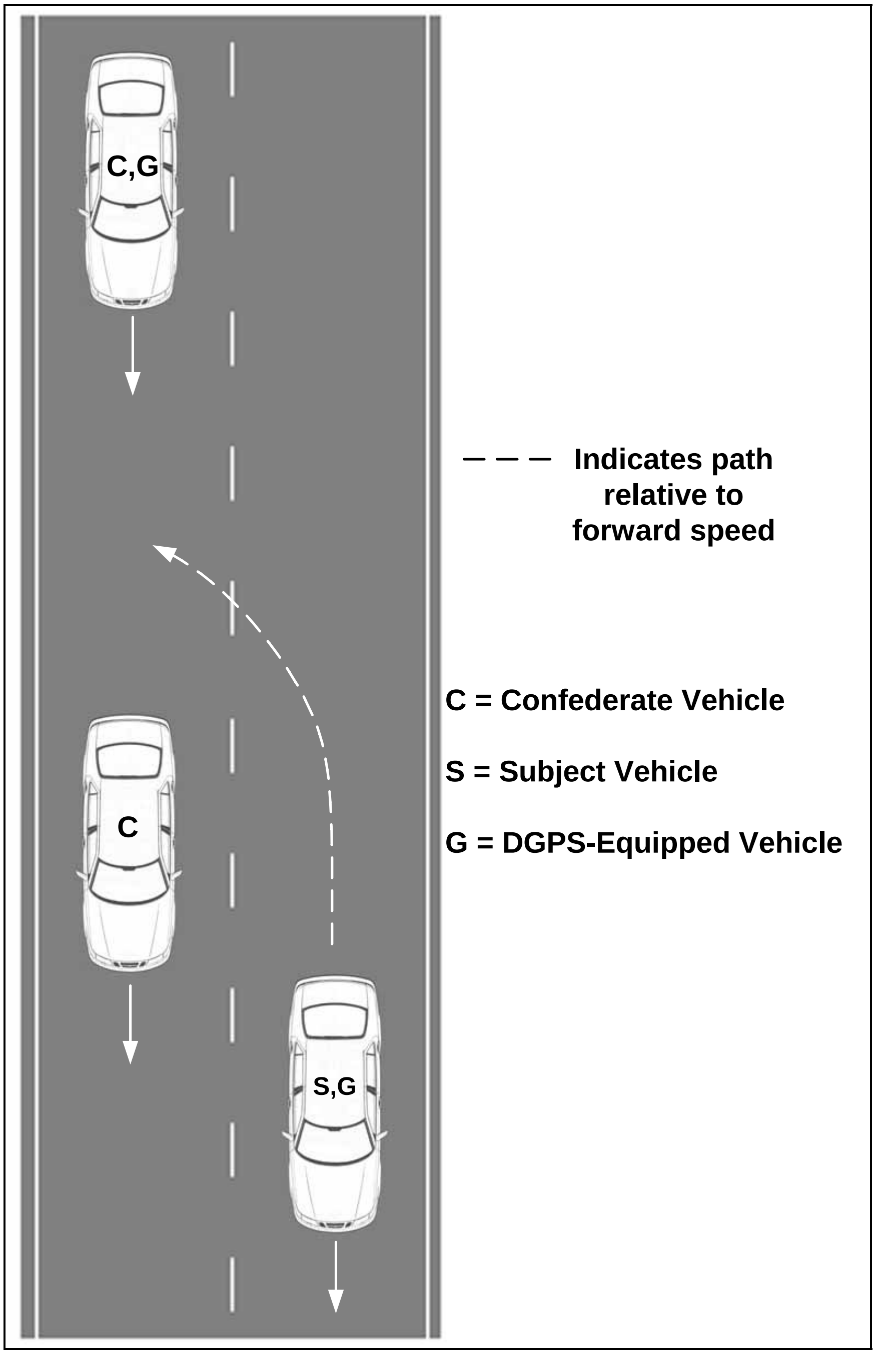


**Figure 51. Decelerating merge maneuver; confederates initially behind the subject. Passenger-side mirror test. (Distances are not to scale.)**

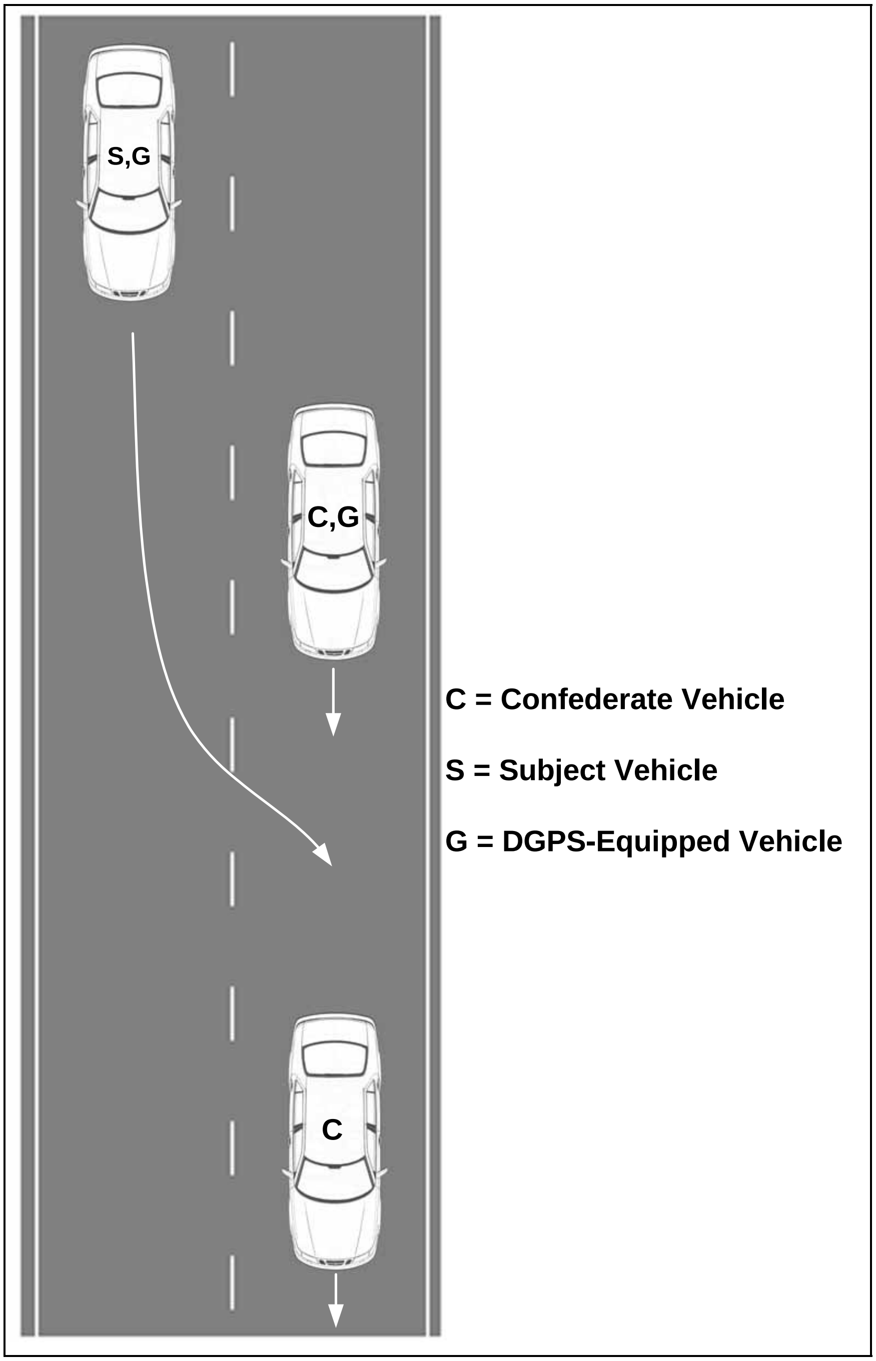


**Figure 52. Accelerating merge maneuver; confederates initially ahead of subject.**
**Driver-side mirror test.**
**(Distances are not to scale.)**

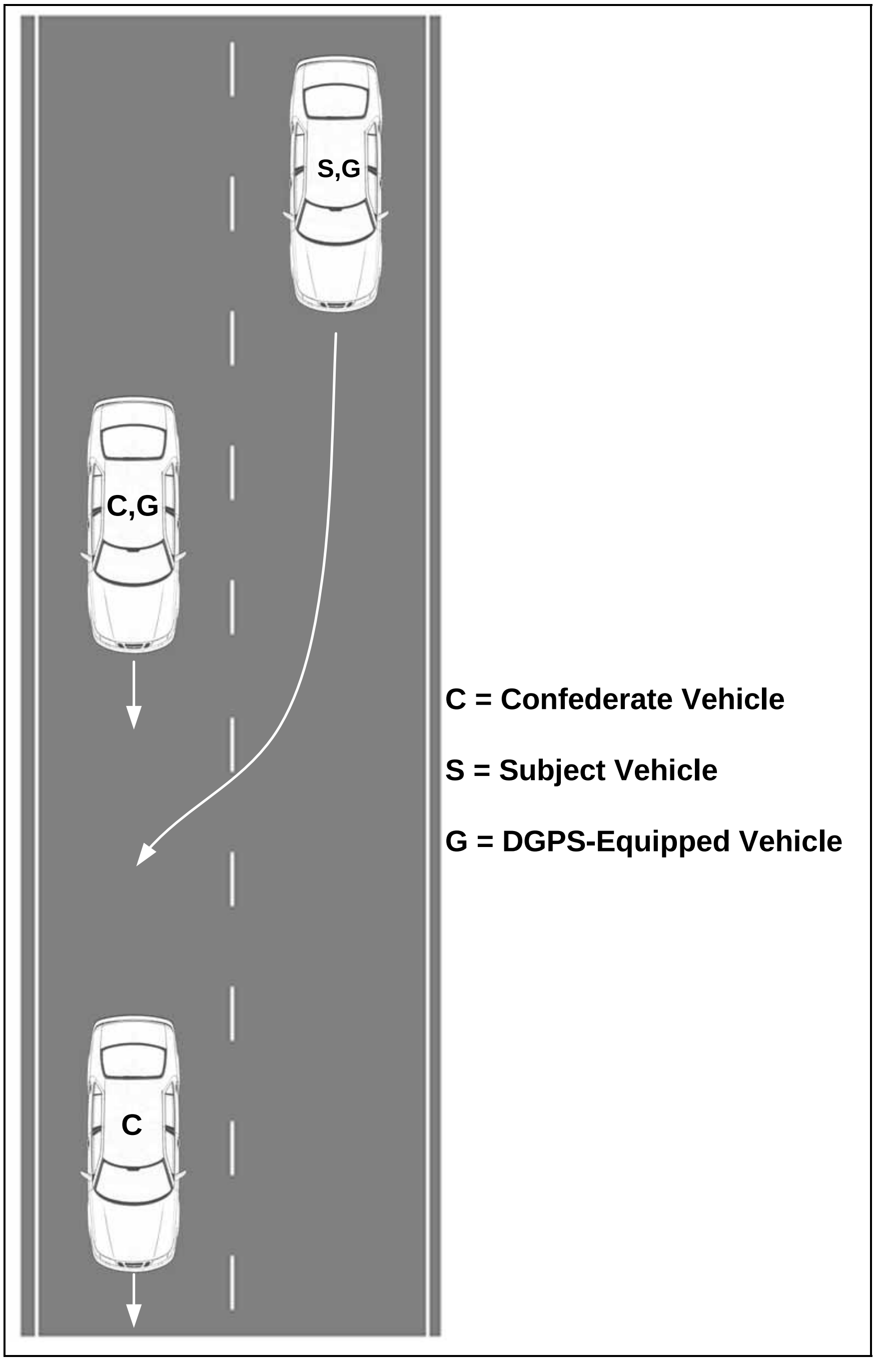


**Figure 53. Accelerating merge maneuver; confederates initially ahead of subject. Passenger-side mirror test.
(Distances are not to scale.)**

The inbound leg was devoted to last comfortable gap, with the scenario as depicted in Figures 54 and 55 for the driver-side and passenger-side mirrors respectively. To provide a degree of driver workload, a car-following task was used. One of the confederate vehicles initially moved to a position 125 ft (38.1 m) in front of the subject vehicle. The subject was instructed to maintain this distance during the entire inbound leg. After the lead confederate vehicle and the subject vehicle reached a steady-state speed of 30 mph (48.3 km/h), the second confederate vehicle approached in the adjacent lane at a speed of 40 mph (64.4 km/h). The subject was instructed to press the button on the right-hand stalk just behind the steering wheel to designate the last comfortable gap. The pushbutton could be activated without removing the right hand from the steering wheel (Figure 56). When the pushbutton was activated, a tone was provided to the driver and a flag was recorded in the data gathering. The purpose of the tone was to ensure that the driver pushed the button sufficiently for activation.

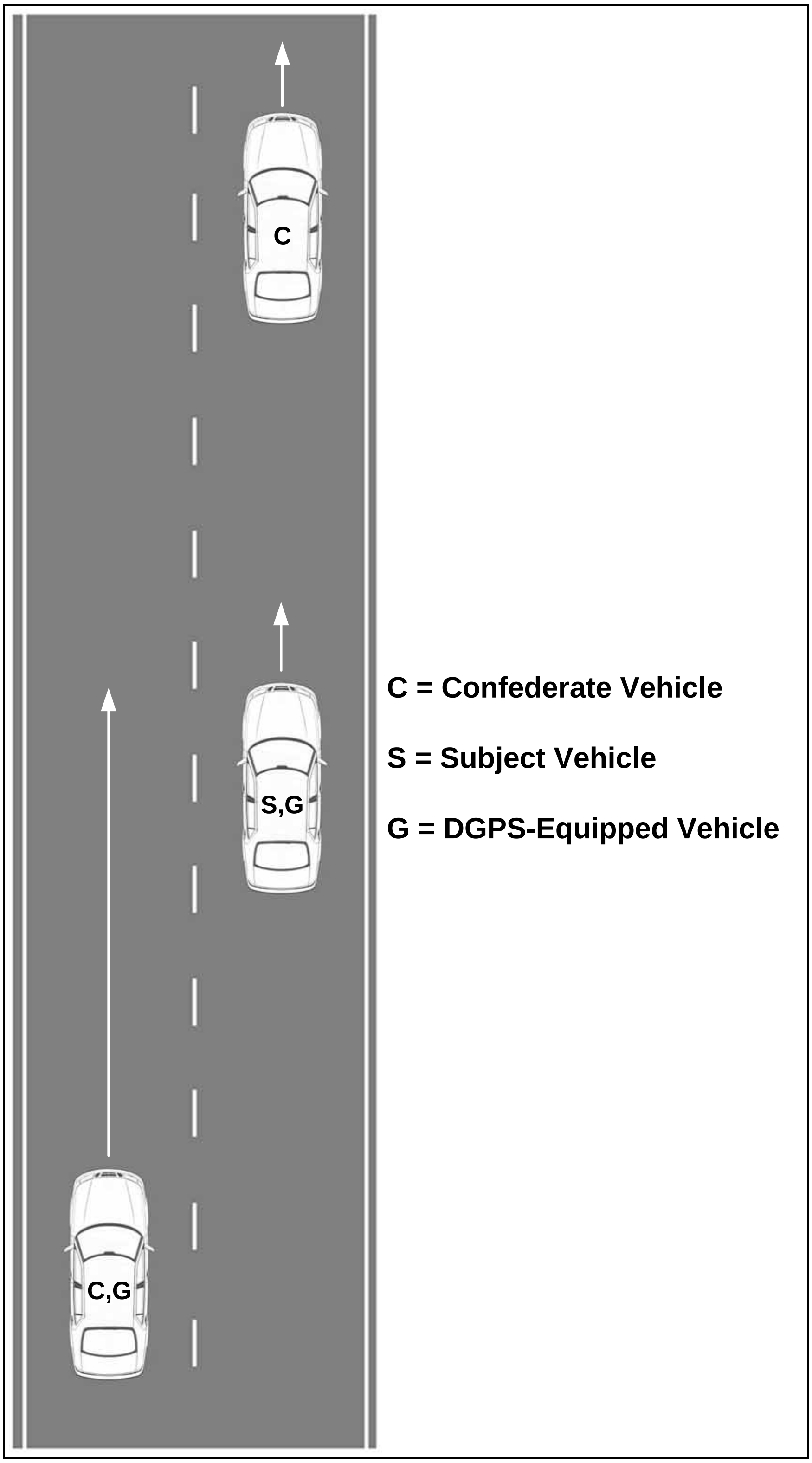


**Figure 54. Last-comfortable-gap determination. Driver-side mirror test. (Distances are not to scale.)**

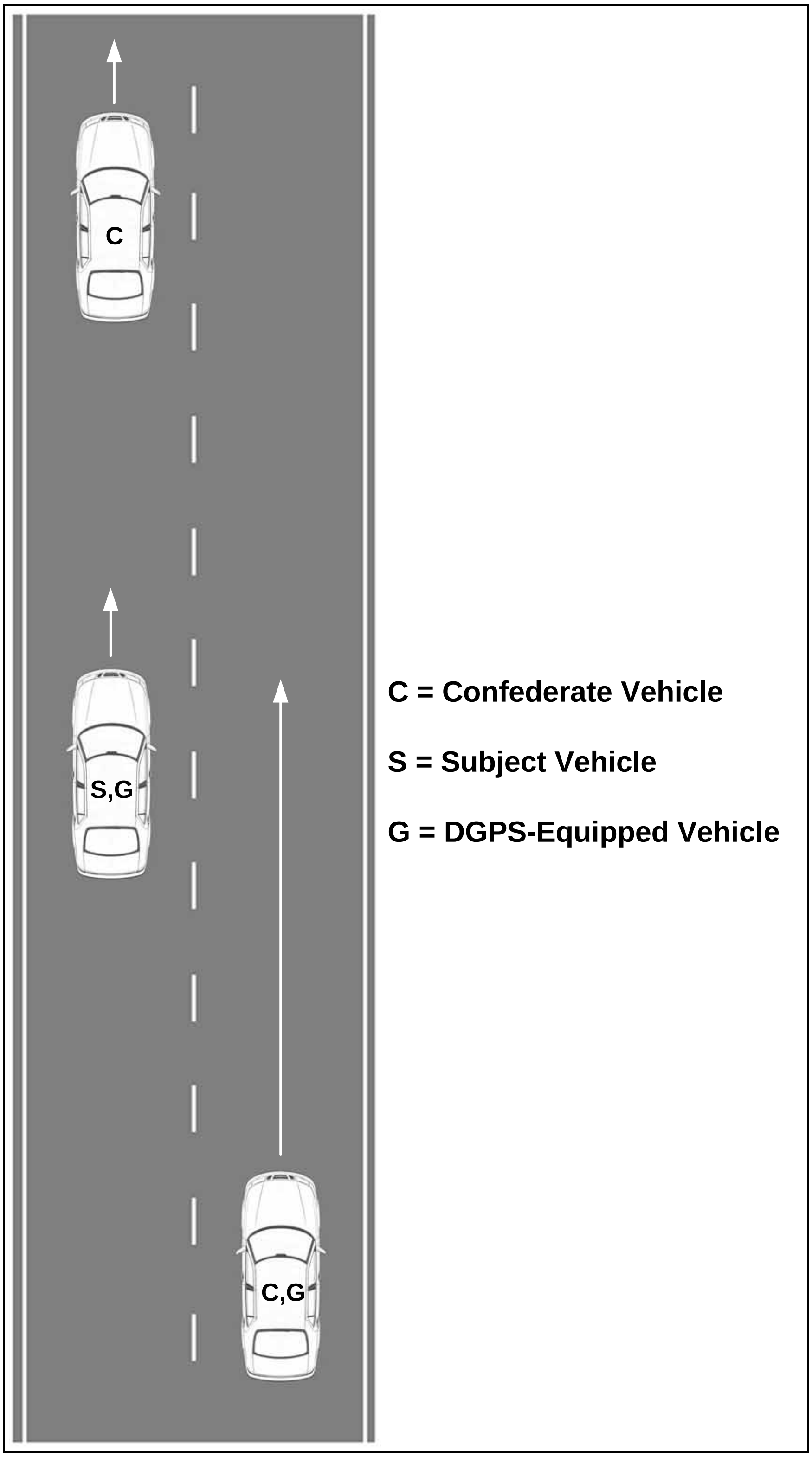


**Figure 55. Last-comfortable-gap determination. Passenger-side mirror test. (Distances are not to scale.)**


**Figure 56. Pushbutton used by the subject in the last-comfortable-gap experiment.**

Last comfortable gap was defined as follows for the 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.
>
> You could assume that you want to change lanes for any reason, but a car is overtaking you in the lane you want to enter. You should press the pushbutton at the last moment when you would feel comfortable moving into the adjacent lane in front of the overtaking vehicle, even if you must speed up.
>
> Please note that you **should not** actually make the lane change. Just press the button to indicate your estimate of last comfortable gap.

Four replications of the last-comfortable-gap experiment were performed on the inbound leg. Between each replication the overtaking confederate vehicle would drop back and then approach from a starting distance of approximately 400 ft (121.9m).

*Scenario Sequence*

Figure 57 portrays the scenario for each mirror evaluation. As mentioned, two full loops of the Smart Road were used for each mirror evaluation. Data was taken during each outbound leg and each inbound leg.

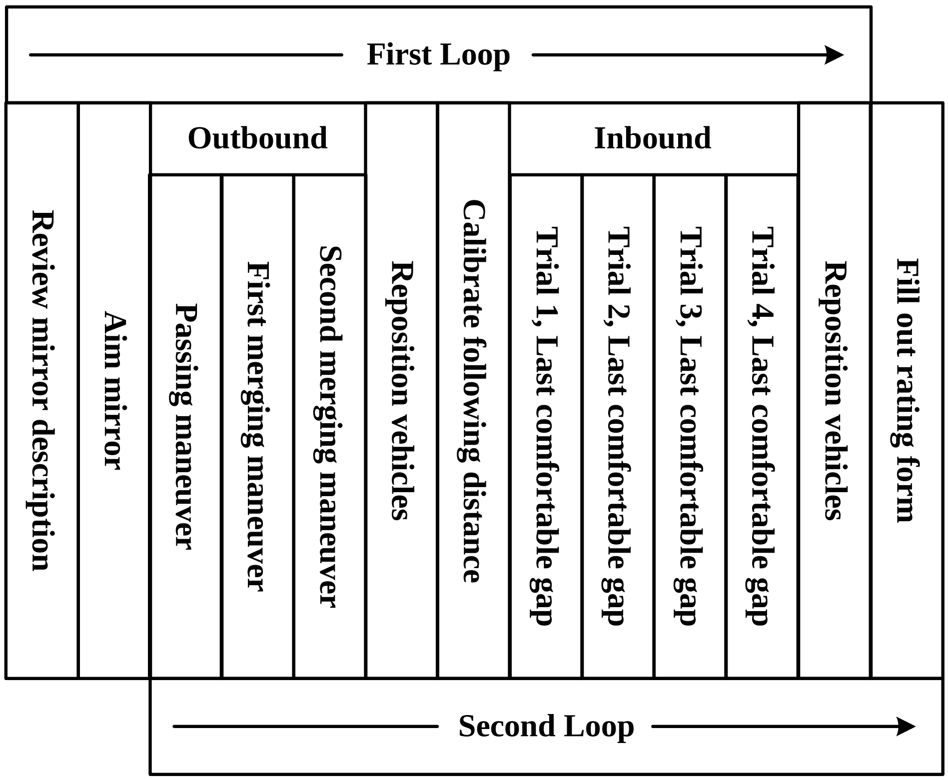


**Figure 57. Experimental scenario for each mirror.**

## Other Details and Practice

As mentioned, each run was composed of two full loops of the Smart Road. Thus, there were 14 data-taking loops for subjects using the driver-side mirrors, and there were 10 data-taking loops for subjects using the passenger-side mirrors. Because the procedures were relatively complex, a single practice loop (first mirror only) preceded the data-taking loops. This loop helped the subject to become acclimatized to the procedure.

During the practice loop, the outside rear-view mirror used was the same as the first mirror that the subject used during data taking. This is equivalent to saying that the subject had three loops of the Smart Road for the first mirror and two loops for all following mirrors. During the first loop, no data were taken. Mirror order of presentation for data taking was counterbalanced across subjects in such a way that each mirror appeared first for two different subjects. Thus, practice for the mirrors was equalized across subjects.

As Figure 57 indicates, after completing the second (data-taking) loop, the subject performed an evaluation of the specific mirror (in combination with the inside rear-view mirror), using a ratings form with several rating dimensions (Appendix B). The ratings were obtained while the vehicle was standing at the starting point (of the outbound loop) for the next run. Once the evaluations were completed, the next outside rear-view mirror was installed, aimed, and described. This process continued until all seven mirrors on the driver side, or all five mirrors on the passenger side had been evaluated.

Each mirror test took approximately half an hour, so that total data-taking time for one subject was approximately four hours for driver-side subjects and three hours for passenger-side subjects. A break was scheduled after four runs on the driver side and three runs on the passenger side.

### Experimental Design

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). As it turned out, the younger driver-side subjects ranged in age from 20 to 29 and the older subjects ranged in age from 67 to 81. For the passenger side, subjects ranged from 19 to 30 in the younger age group and 66 to 75 in the older age group. 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

The main instrumentation for this experiment was installed in the subject vehicle and one of the confederate vehicles. Included in the subject vehicle was 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 interface to store data as they were gathered.

The 12 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. Changeover by the experimenter and aiming by the subject was generally accomplished in approximately three minutes.

The elongated mirrors described earlier used a light-weight spacer between the back of the mirror and the attaching tape. The reason for this was that the mirrors were too large to fit into the mirror housings of the vehicle. The spacers allowed these longer mirrors to be adjusted with the usual in-vehicle (remote) controls.

The camera system is depicted in Figure 58. It 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. As the figure shows, 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 was aimed into the driver side adjacent lane and the other was aimed into the passenger 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.

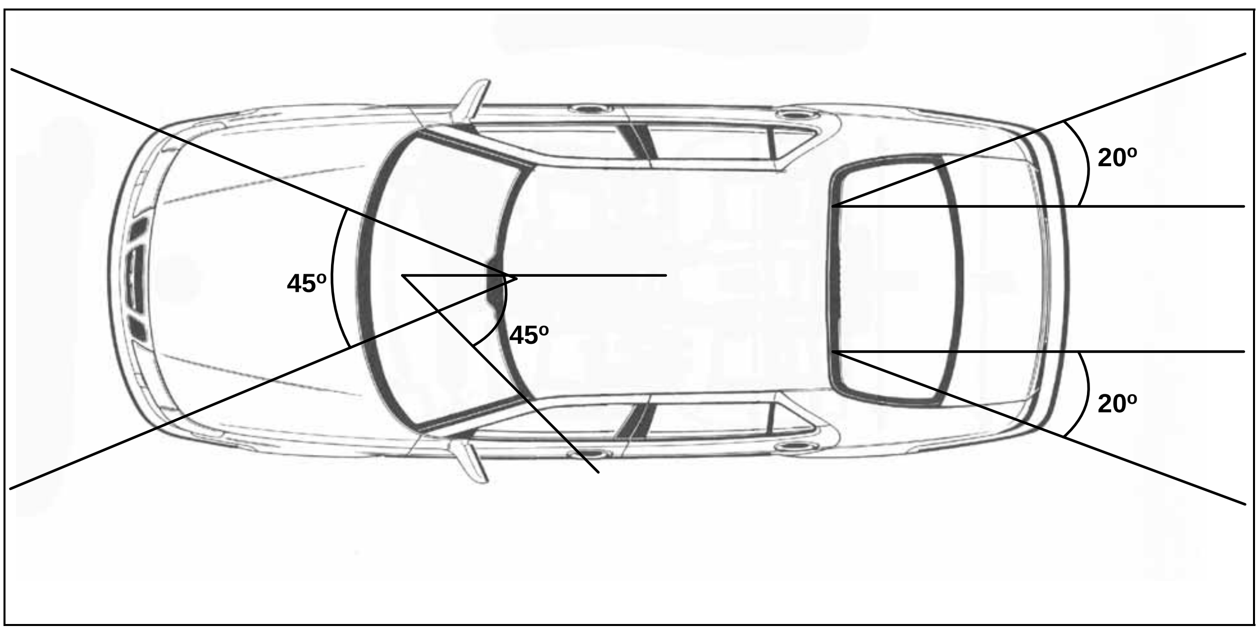


**Figure 58. Video camera locations in the subject vehicle.**

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.

As mentioned, coordination of the three vehicles involved in the experiment was accomplished by voice radio communications, with the experimenter in the subject 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 speeds, distances, and 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 unobtrusive. Thus, the driving environment appeared relatively natural to the subject.

**Measures**

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 at least 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 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. Two ratings were obtained to assess the combined usage of each outside rear-view mirror in combination with the interior rear-view mirror, and four ratings were obtained that assessed each outside rear view mirror more or less by itself (see Appendix B). In regard to combined usage, the corresponding two ratings involved Coordination and Speed/Distance Estimation. In regard to the outside rear-view mirror itself, the four ratings were Field-of-View, Distortion, Uneasiness, and Comfort Level. 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.

As the ratings form shows, 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 the baselines.

### Preliminary Subject Instructions and Procedures

Upon arrival, the subject read and signed an informed consent form, assuming 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 (Appendix C). Thereafter 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 (Appendix D).

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 might not have been able to accurately evaluate how well the mirrors performed. Except for size, their general appearance was quite similar.

The ratings form (Appendix B) was also shown and explained to each 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 (described earlier in this chapter). The experimenter and the subject discussed last comfortable gap until it was clear that the subject fully understood the concept.

### Additional Instructions and Procedures at the Beginning of the Outbound and Inbound Legs

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 other vehicles would be 30 mph (48.3 km/h). 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. 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.

### Summary of Goals of the Dynamic Tests

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 in the United States?

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? Which mirrors, if any, from the driver's standpoint are preferred?

5. 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.

# CHAPTER 19. RESULTS, DISCUSSION, AND CONCLUSIONS ASSOCIATED WITH THE ON-ROAD EXPERIMENT

## Introduction

The analyses for the road tests were carried out in three parts: The first part involved performance and eyeglance analysis for the passing and merging tasks. The second part involved performance and eyeglance analysis for the last-comfortable-gap task. The third part involved analysis of the opinion data, which were gathered for each mirror following the tests with that mirror. Consequently, the opinion data are based on each driver's (subject's) total experience with the specific mirror.

Results of the various analyses are presented in this chapter. Because there are so many results, they are presented in brief form. Wherever possible, results are shown in graphical form. This procedure has been used so that the chapter could be kept to a manageable length.

## Analyses Associated with the Passing and Merging Tasks

For each side of the vehicle there were two replications each of the passing task (Figures 48 and 49), two replications of the decelerating merge task (Figures 50 and 51), and two replications of the accelerating merge task (Figures 52 and 53). The performance data were analyzed for initiation of cut-in distance between the subject's vehicle and the DGPS-equipped confederate's vehicle. The idea was to determine how the various mirrors affected gap acceptance, as determined by cut-in initiation distance.

For mirrors on the driver side of the vehicle, cut-in distances were analyzed using an ANOVA with Mirror type, Age group, Gender, and Event as independent variables. The Event variable had six levels designated as follows: first passing maneuver (1P), first decelerating merge (1DM), first accelerating merge (1AM), second passing maneuver (2P), second decelerating merge (2DM), and second accelerating merge (2AM). Mirror and Event were within subject variables. Results demonstrated a significant Event main effect, $F(5,120) = 546$, $p < 0.0001$ and a significant Mirror main effect, $F(6,143) = 2.51$, $p = 0.0241$. There were no other significant main effects or interactions. Figure 59 shows a plot of the Event mean values. In the plot, values with a common letter do not differ significantly ($\alpha = 0.05$) using the SNK test. The results show that the decelerating merge maneuvers differed significantly from the passing maneuvers and the accelerating merge maneuvers. It is believed that this difference occurred because of the subject referencing to (and attempting to clear) the back end of the lead confederate vehicle in the decelerating merge. This would cause the distance to the *rear* confederate vehicle, which was DGPS-equipped, to be quite large, as is demonstrated in the plot of Figure 59.

The plot shows that the decelerating merge cut-in distance was 149.5 ft (45.6 m) on average. This value was compared to the mean actual distance between the lead and rear confederate vehicles. This calculation was done after the experiment using videotape time markings and DGPS values between the subject vehicle and the rear confederate vehicle when the subject vehicle was alongside the lead confederate vehicle. The resulting mean distance between the two confederate vehicles was 195.2 ft (59.5 m). Adding the length of the subject vehicle to the mean cut-in distance and then subtracting the result from the mean distance between the two confederate vehicles results in an approximate mean cut-in distance behind the lead confederate vehicle of 29.7 ft (9.05 m), a value that is similar to the cut-in distances for the passing merge and the accelerating merge.

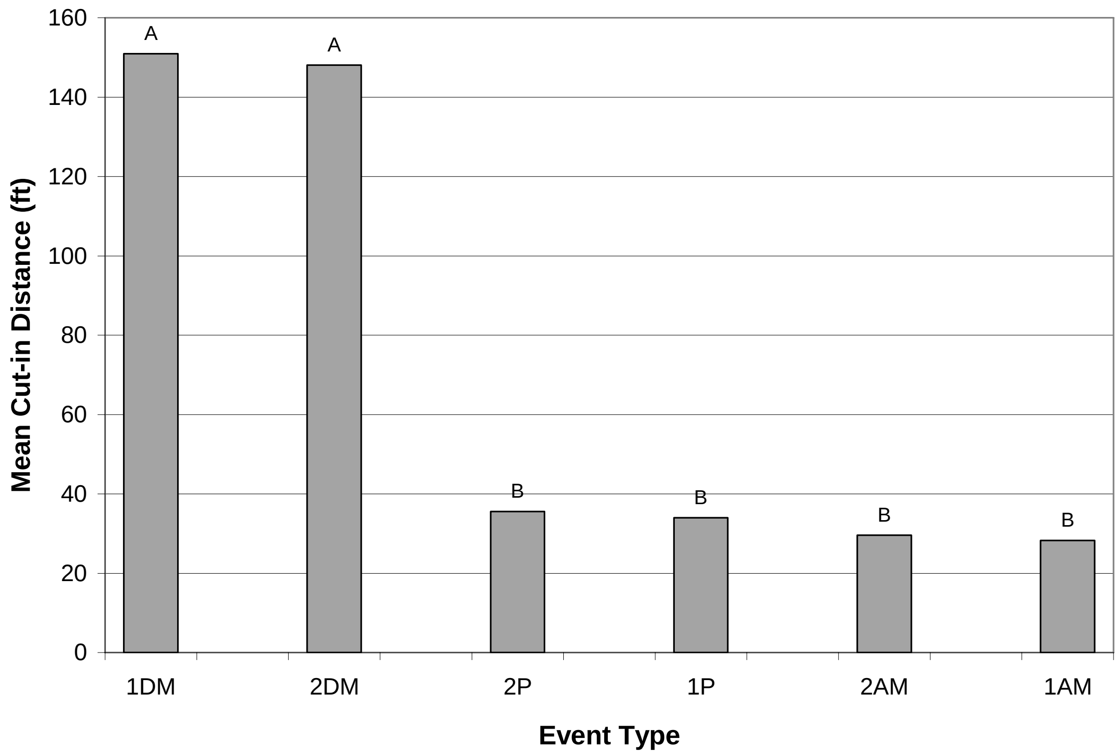


**Figure 59. Mean cut-in distance for the various passing and merging events, driver side.**

For the Mirror main effect, the results are plotted in Figure 60 by mirror type. Again, means with a common letter do not differ significantly using the SNK test. These results show that the flat elongated mirror (F-E) produced the most conservative mean cut-in distance, followed by the conventional flat mirror (F). However, the conventional flat mirror and the aspheric mirrors do not differ significantly. In fact, all of the mirrors produce mean cut-in distances within 7.7 ft (2.35 m) of one another.

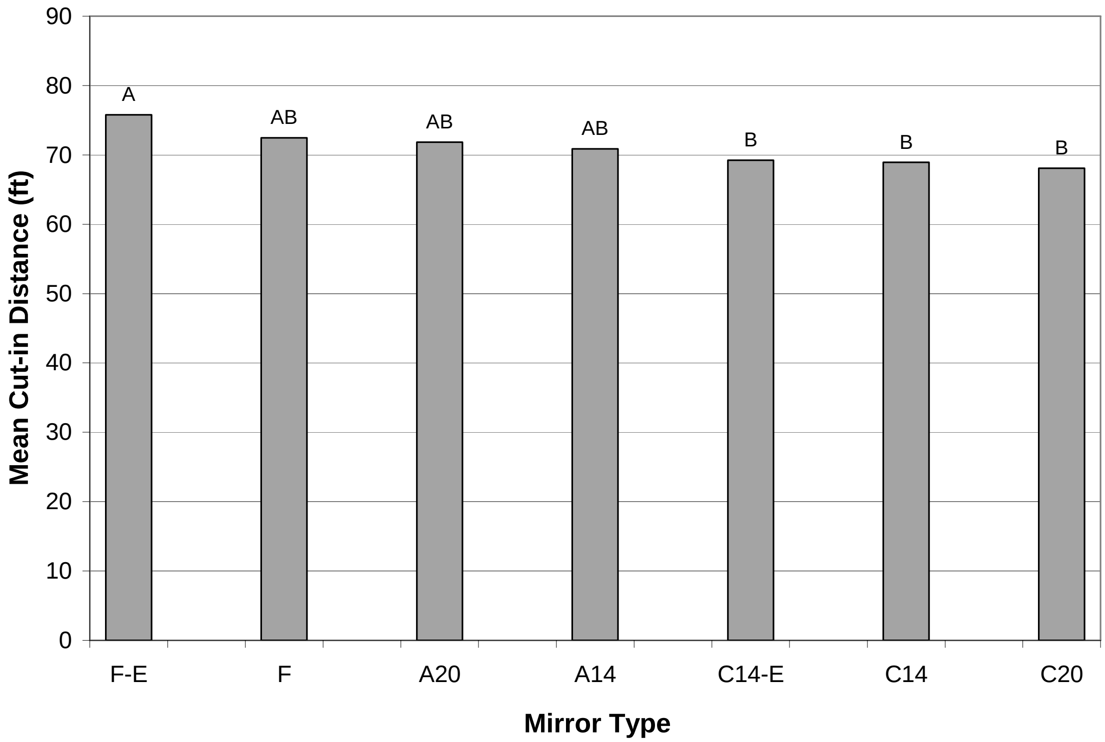


**Figure 60. Mean cut-in distance as a function of mirror type, driver side.**

In similar fashion, the passenger side cut-in distances were analyzed using an ANOVA with the same set of independent variables. In this case, Mirror had five levels instead of seven. Once again there were significant main effects of Event, $F(5,80) = 467$, $p < 0.0001$, and Mirror, $F(4,64) = 4.62$, $p = 0.0024$. In addition there were two significant interactions: Age group by Event, $F(5,80) = 3.88$, $p = 0.0034$, and mirror by Event, $F(20,320) = 2.35$, $p = 0.0011$.

Figure 61 shows the mean cut-in distances as a function of passing/merging maneuver type. The results are quite similar to those for the driver side; however, all cut-in distances are somewhat larger. Once again the decelerating merges had significantly larger cut-in distances because subjects apparently attempted to clear the rear of the lead confederate vehicle.

The mean cut-in distance to the rear confederate vehicle for the decelerating merges was 171.0 ft (52.1 m). A calculation was again carried out to determine mean cut-in distance relative to the lead vehicle. The mean distance between the two confederate vehicles was calculated and found to be 210.1 ft (64.0 m). Thus, mean clearance referenced to the lead confederate vehicle at the initiation of cut-in was determined to be 23.1 ft (7.04 m) (a relatively short cut-in distance, which the experimenter in the subject vehicle verified based on his observations). Note that this cut-in distance is less than the other cut-in distances shown in Figure 61.

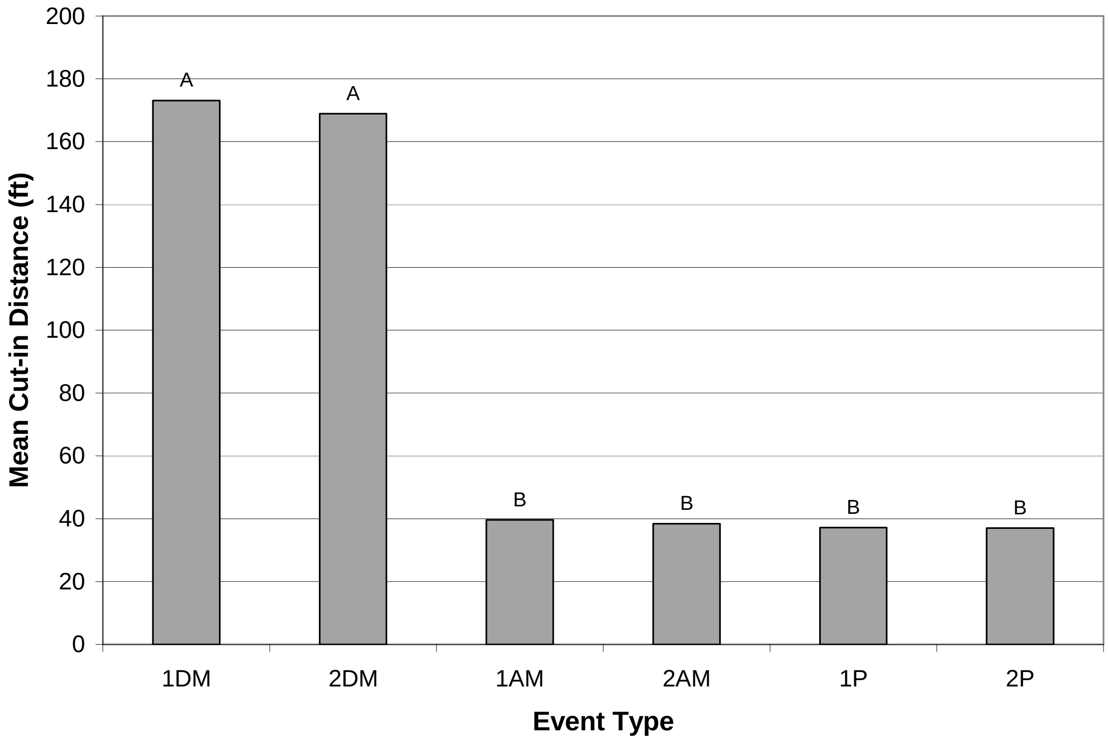


**Figure 61. Mean cut-in Distance for the various passing and merging events, passenger side.**

In terms of cut-in distance as a function of mirror type, the results are plotted in Figure 62. The C-14 mirror had a significantly shorter mean cut-in distance than all other mirrors. Note that this mirror is in common use on today's automobiles. Note also that once again the range of mean cut-in distances for the mirrors is only 6.4 ft (1.95 m), a result that is quite similar to that on the driver side.

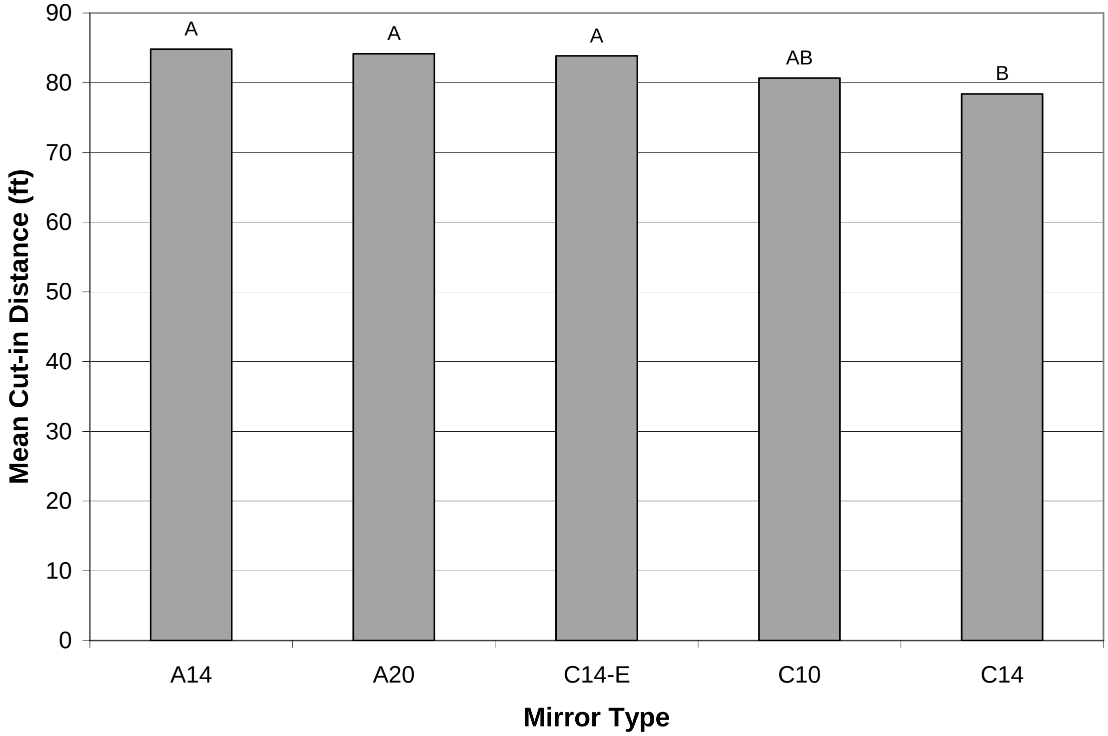


**Figure 62. Mean cut-in distance as a function of mirror type, passenger side.**

The interaction of Age group and event is shown in Figure 63. As the figure shows, older subjects had *less* conservative cut-in distances. Note that for the decelerating merge, the larger distances to the rear confederate (DGPS-equipped) vehicle would correspond to shorter cut-in distances behind the lead confederate vehicle. Thus, all cut-in means for older subjects are less conservative.

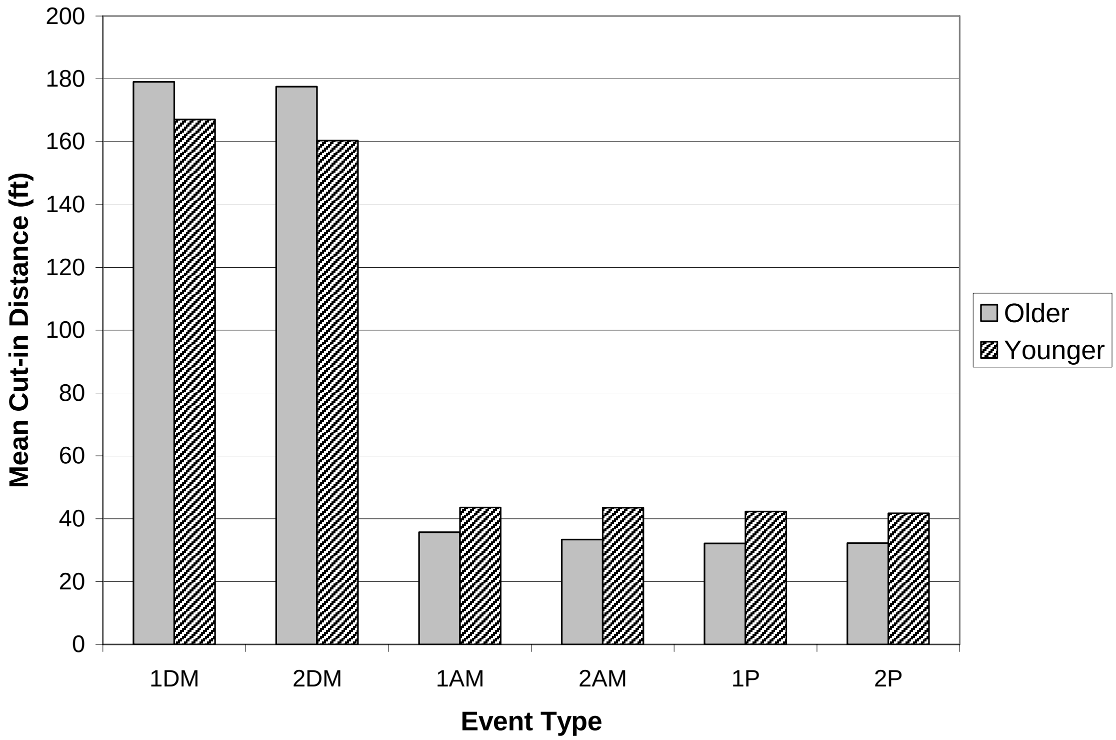


**Figure 63. Interaction of mean cut-in distance as a function of age and event type, passenger side.**

The mirror by event interaction is plotted in Figure 64. As can be seen, the C14-E mirror generally produced the least conservative results. This mirror does not show up as less conservative in the mirror main effect (Figure 62) because of the offsetting measurement differences between the decelerating merges and the other events. In any case, differences due to mirror type are small for each given type of event.

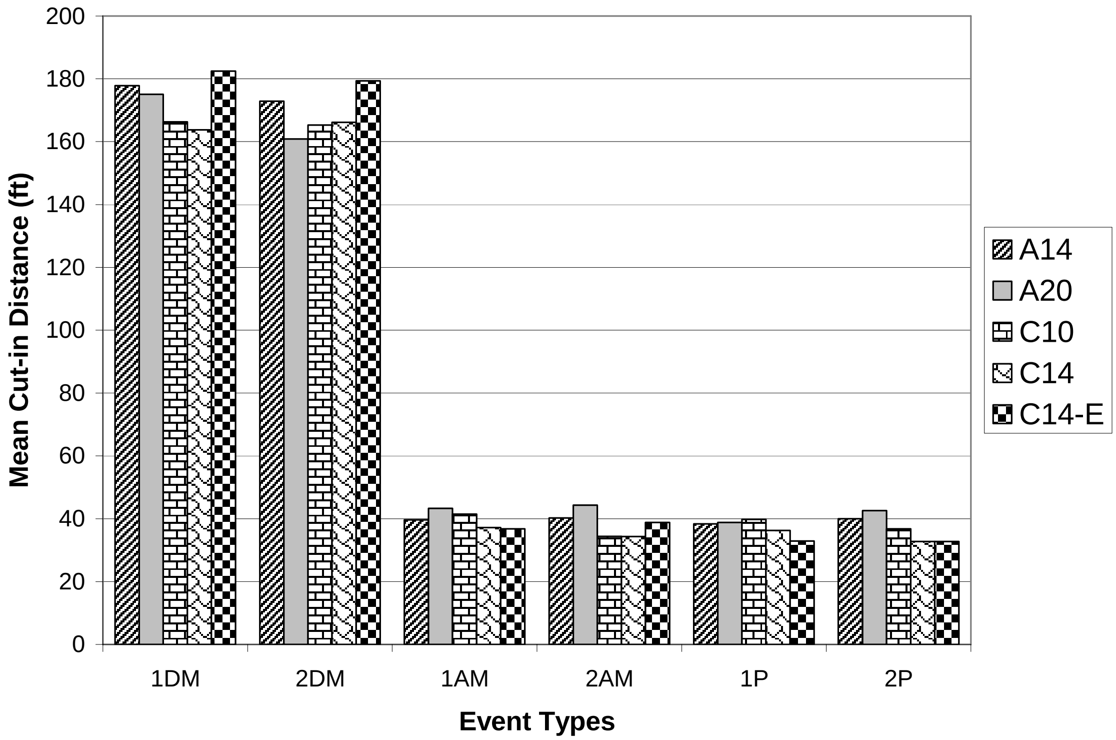


**Figure 64. Interaction of mean cut-in distance as a function of mirror type and event type, passenger side.**

Eyeglance analyses for the merging and passing maneuver events were carried out "by maneuver type" and not by replication. Consequently, there is one distribution plot for each age group for the two passing maneuvers 1P and 2P, one for the decelerating merge maneuvers 1DM and 2DM, and one for the accelerating maneuvers 1AM and 2AM. By combining the eyeglance behavior for the first and second replications, a more stable set of plots could be obtained. Eyeglance behavior represents a method for determining the source from which the driver is gathering information.

Eyeglance data were analyzed for the 10 s just prior to cut-in. It was believed that this time interval represented the most relevant interval in the decision-making process regarding when to execute the cut-in maneuver.

The eyeglance distributions for the passing maneuver on the driver side (refer to earlier Figure 48) are shown in Figures 65, 66, and 67. Figure 65 is for older subjects, Figure 66 is for younger subjects, and Figure 67 is for all subjects (that is, older and younger combined). The only observable trends are that older subjects looked forward somewhat more than younger subjects, while younger subjects used their driver-side mirror more. Figure 67 shows that, overall, there is quite a bit of uniformity in glance patterns as a function of mirror type.

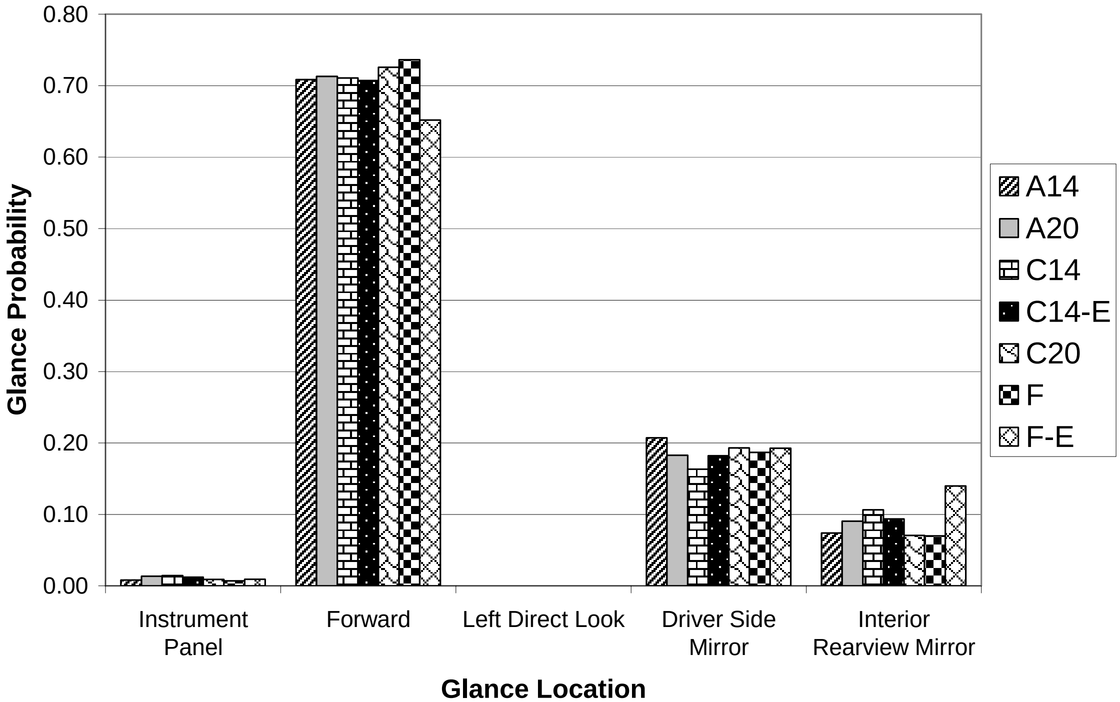


**Figure 65. Glance probabilities for the older subjects as a function of mirror type in the passing maneuver, driver side.**

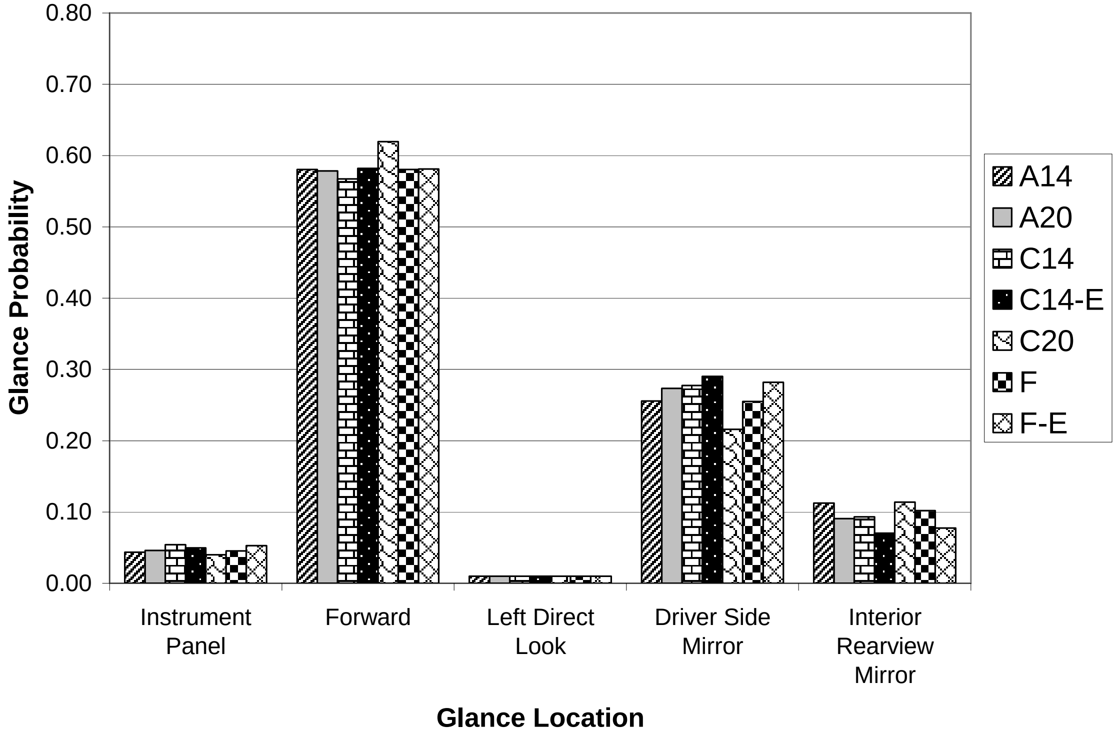


**Figure 66. Glance probabilities for the younger subjects as a function of mirror type in the passing maneuver, driver side.**

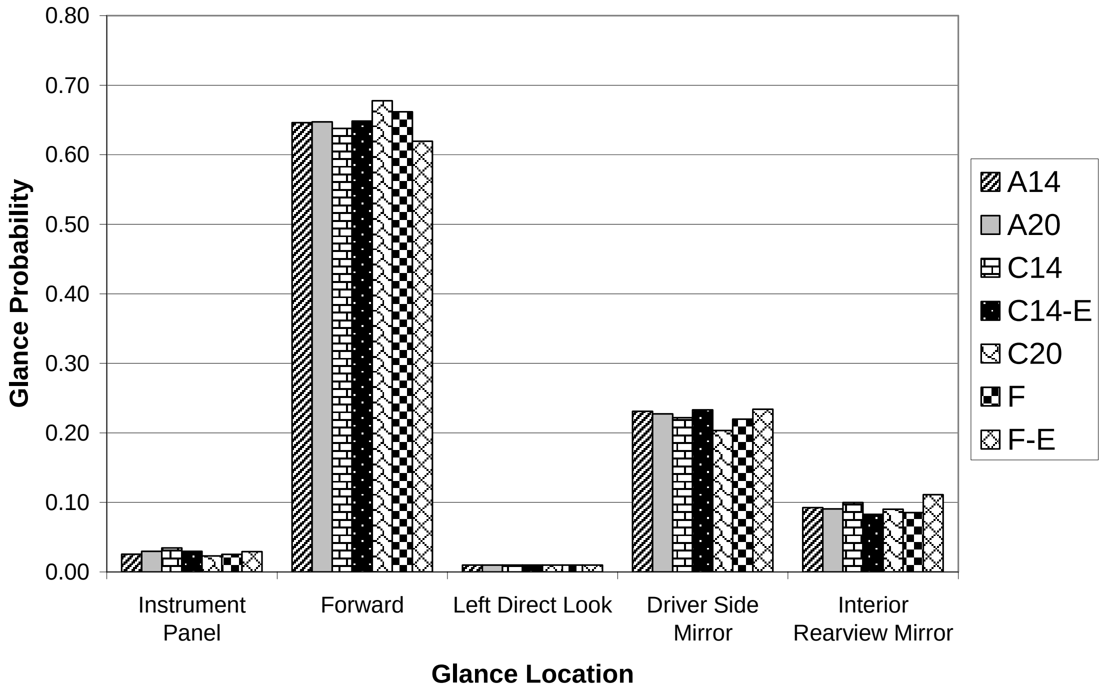


**Figure 67. Glance probabilities for all subjects as a function of mirror type in the passing maneuver, driver side.**

In regard to the driver side decelerating merges (see Figure 50) the eyeglance analysis results are shown in Figures 68, 69, and 70, for older, younger, and all subjects, respectively. Once again the same general trends are seen. Older subjects tended to look forward more of the time. However, both older and younger subjects used the C20 mirror somewhat less than the other mirrors, with older subjects spending the extra time on the forward view and younger subjects spending the extra time on the interior rear-view mirror. All other differences among mirrors are quite small, as can be seen in Figure 70.

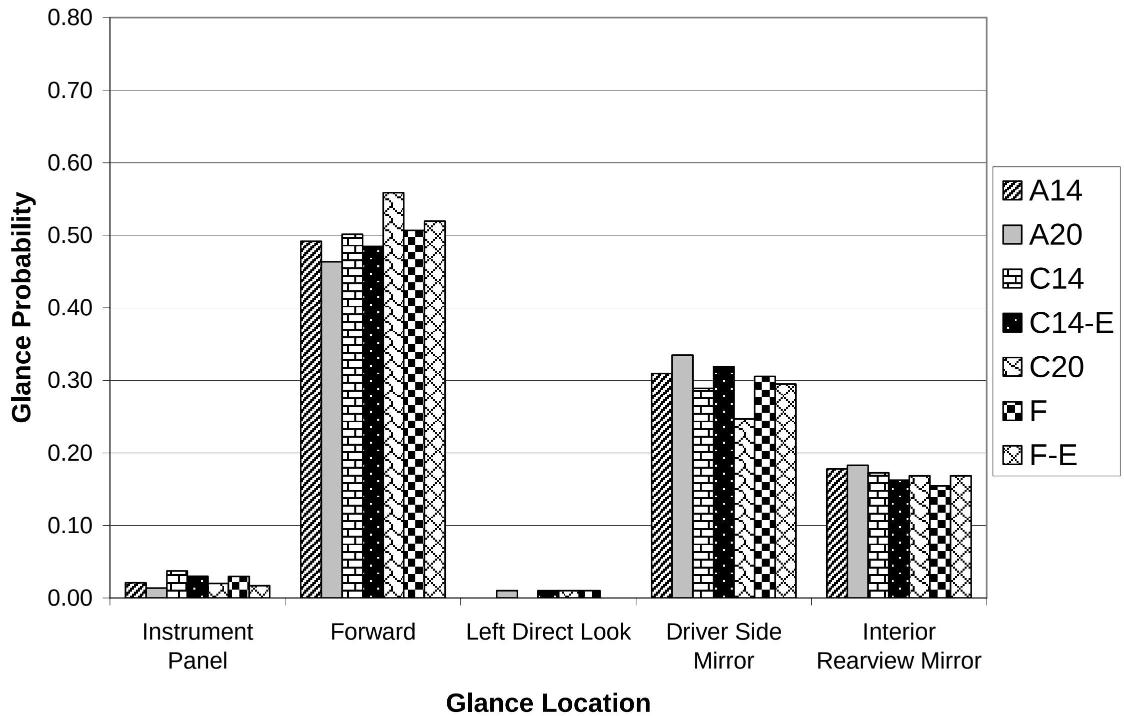


**Figure 68. Glance probabilities for the older subjects as a function of mirror type in the decelerating merge maneuver, driver side.**

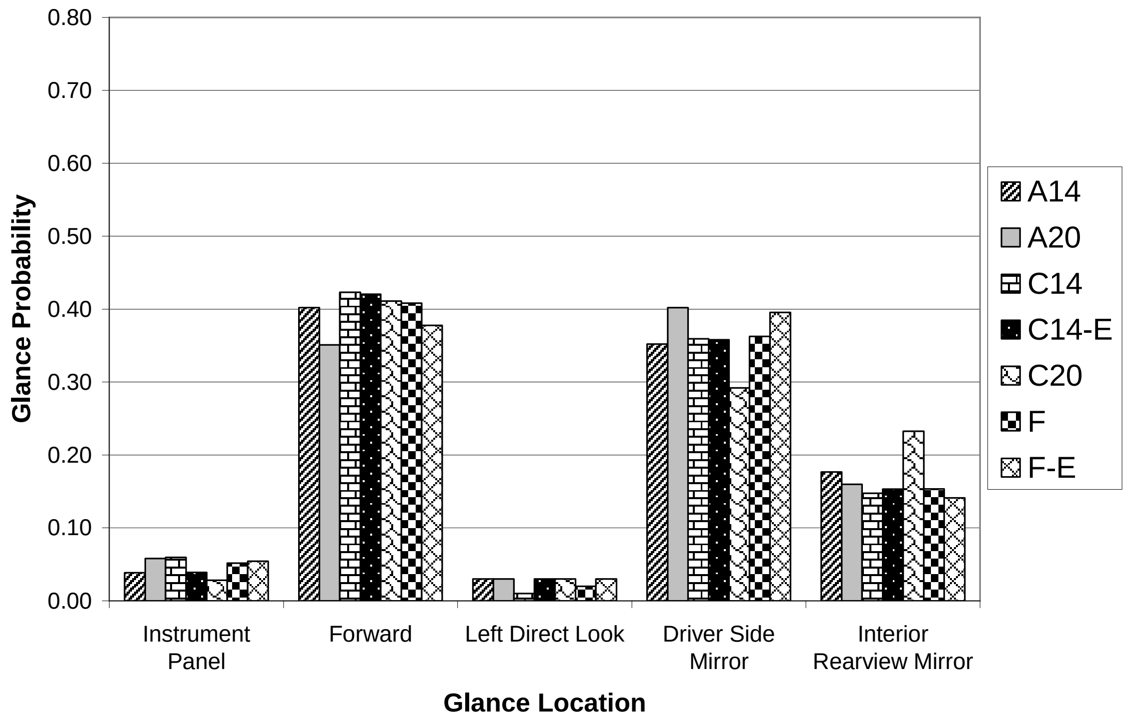


**Figure 69. Glance probabilities for the younger subjects as a function of mirror type in the decelerating merge maneuver, driver side.**

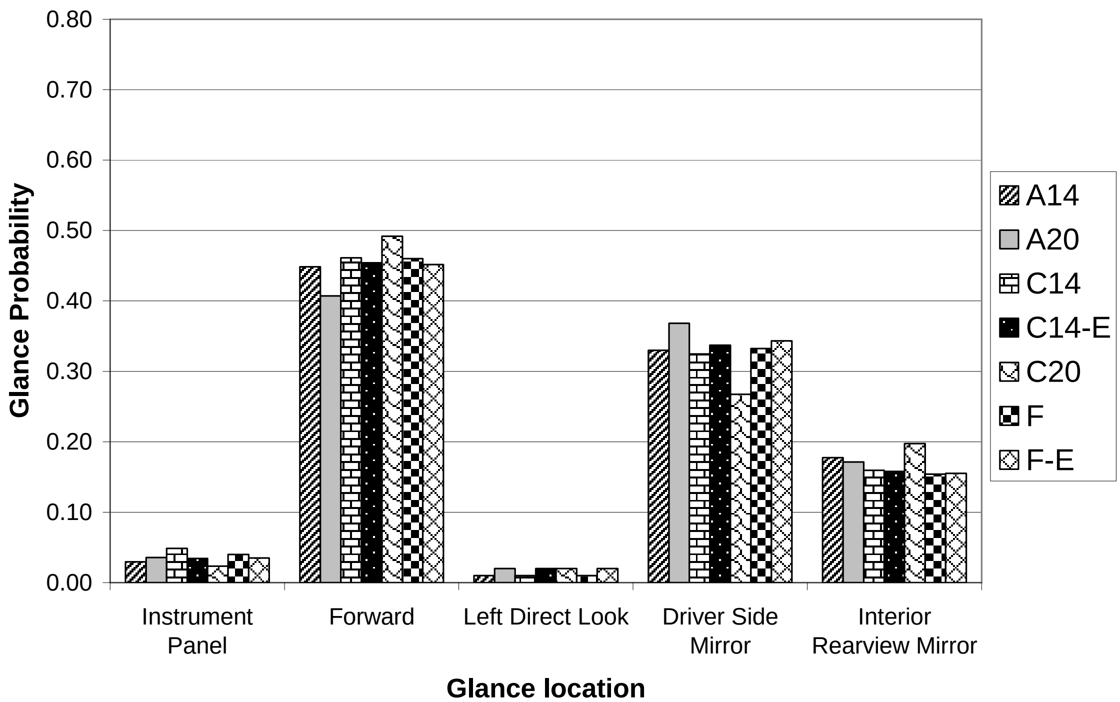


**Figure 70. Glance probabilities for all subjects as a function of mirror type in the decelerating merge maneuver, driver side.**

For the accelerating merge maneuvers on the driver side (see Figure 52), the results are shown in Figures 71, 72, and 73. There is remarkable uniformity across the mirror types and very little difference between older and younger drivers.

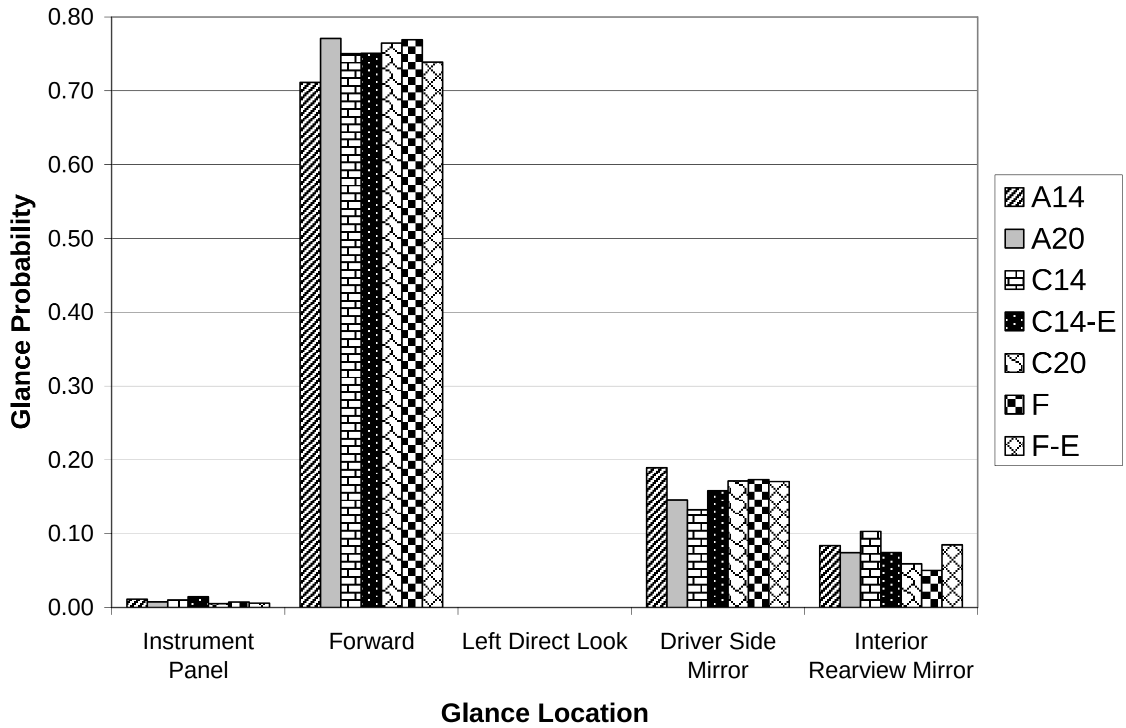


**Figure 71. Glance probabilities for the older subjects as a function of mirror type in the accelerating merge maneuver, driver side.**

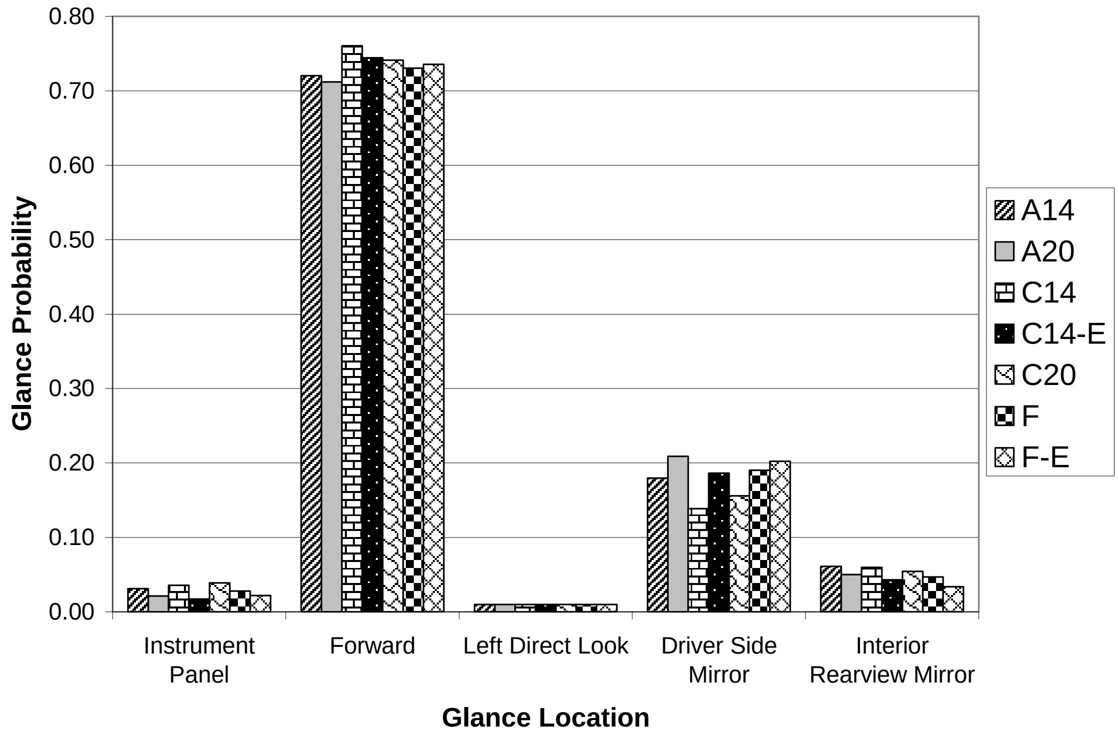


**Figure 72. Glance probabilities for the younger subjects as a function of mirror type in the accelerating merge maneuver, driver side.**

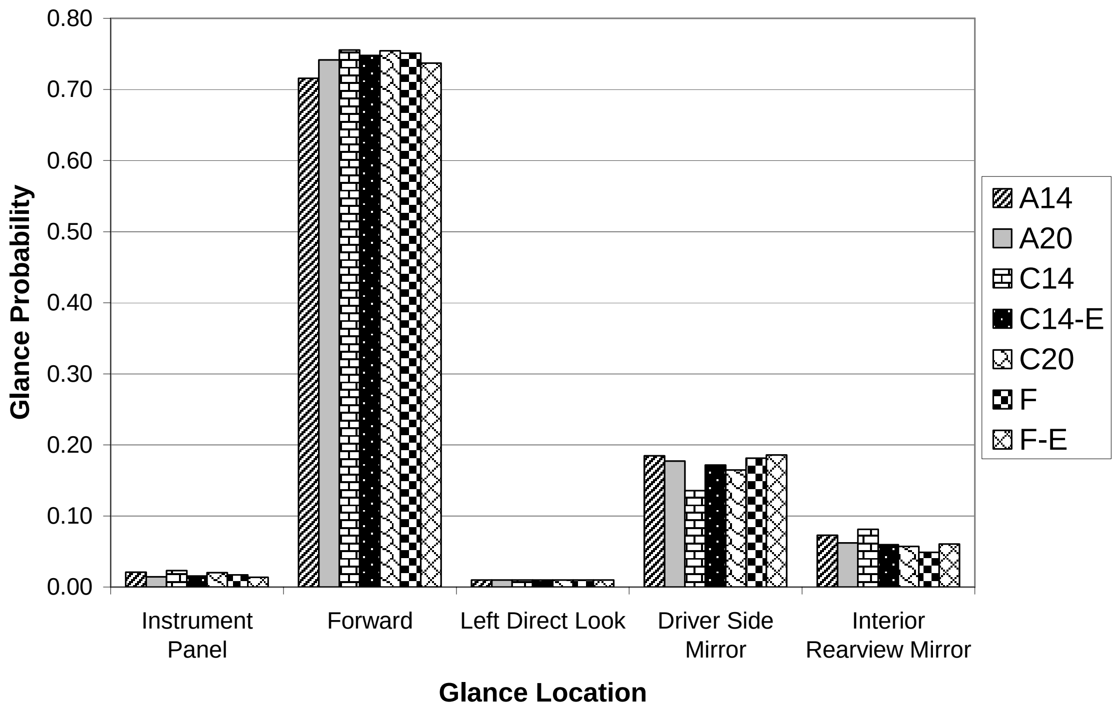


**Figure 73. Glance probabilities for all subjects as a function of mirror type in the accelerating merge maneuver, driver side.**

The passenger-side maneuvers involved five non-planar mirrors, as previously explained. For the passing maneuver on the passenger side (see Figure 49), the results are shown in Figures 74, 75, and 76 for older, younger, and all subjects, respectively. Older drivers tended to use their interior rear-view mirror a bit more, while younger subjects used their driver-side mirror a bit more. Otherwise, differences as a function of mirror type are minor.

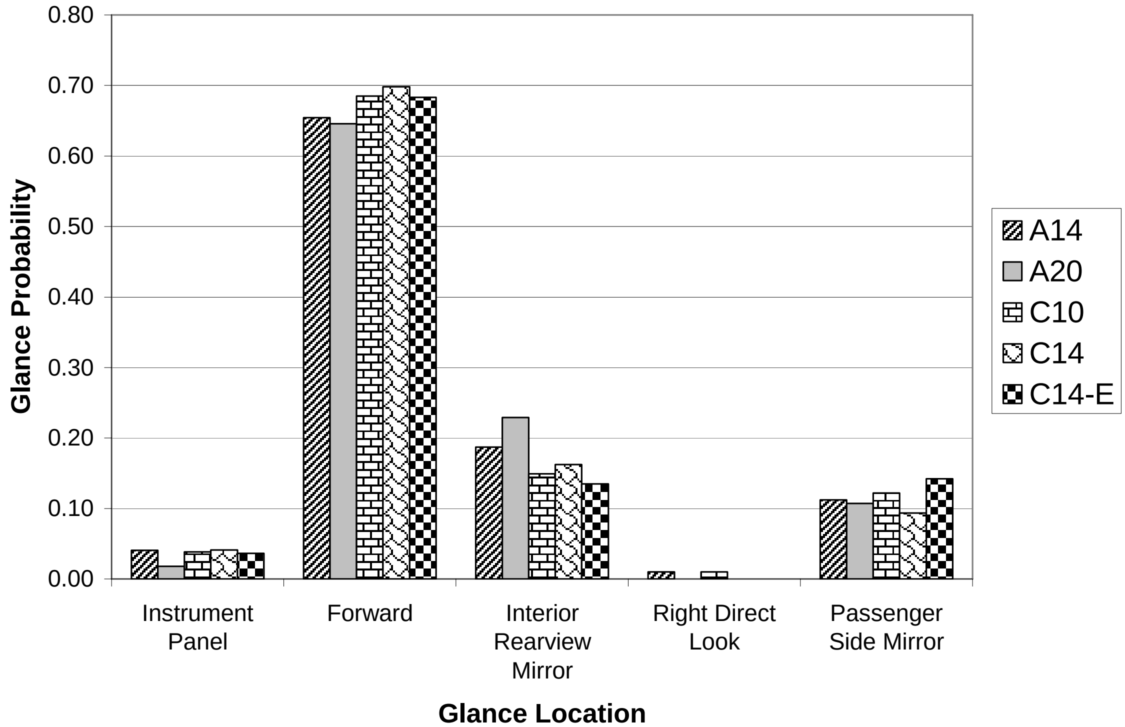


**Figure 74. Glance probabilities for the older subjects as a function of mirror type in the passing maneuver, passenger side.**

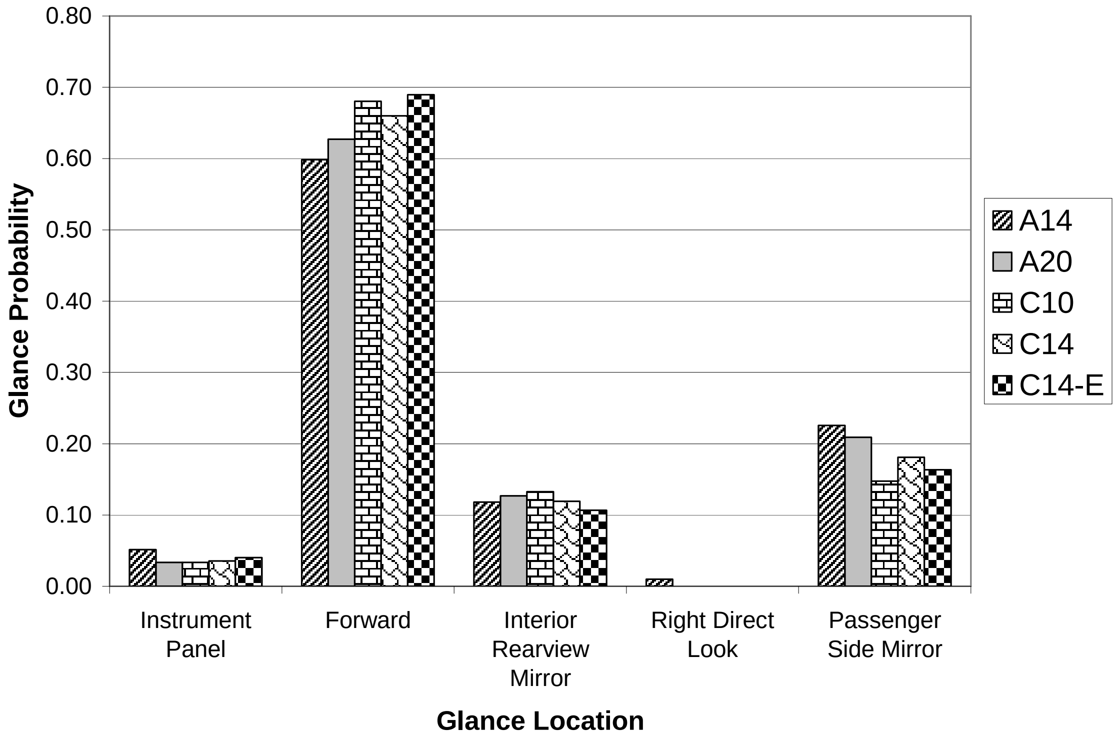


**Figure 75. Glance probabilities for the younger subjects as a function of mirror type in the passing maneuver, passenger side.**

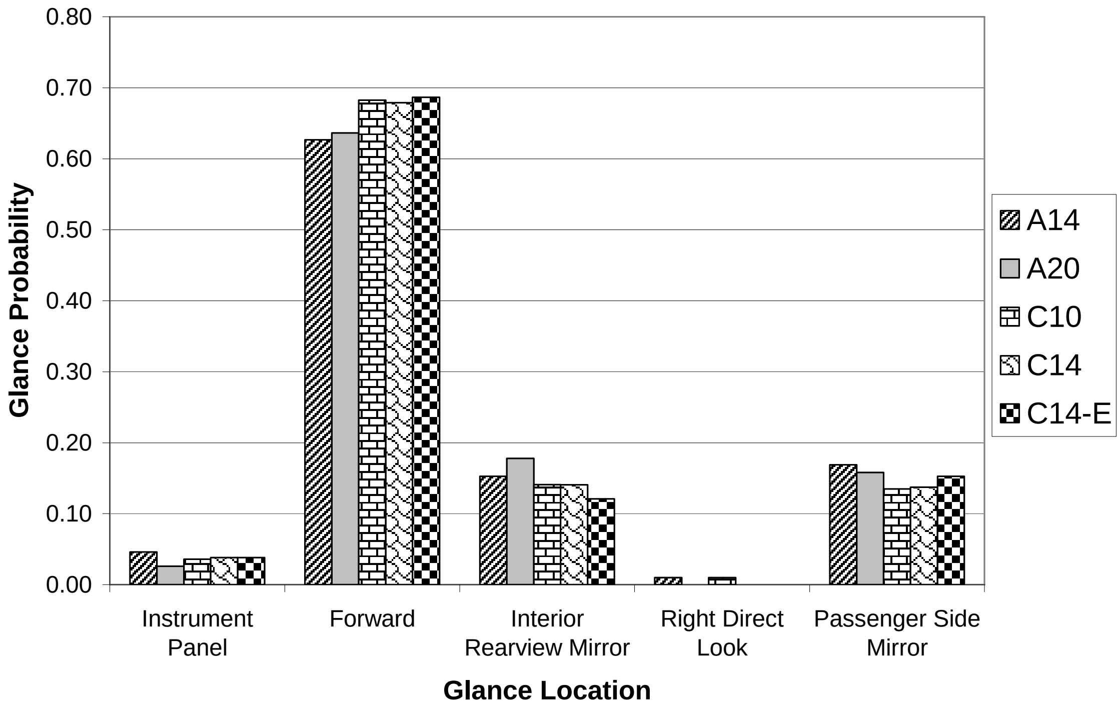


**Figure 76. Glance probabilities for all subjects as a function of mirror type in the passing maneuver, passenger side.**

For the decelerating merge maneuver on the passenger side (corresponding to Figure 51), the results are shown in Figures 77, 78, and 79, for older, younger, and all drivers, respectively. Older subjects relied on the interior rear-view more than younger subjects, while younger subjects spent more time on the forward view. There are some differences in use of the various passenger-side mirrors for younger subjects, but the differences are small. In particular, the C14-E mirror was used a bit less than the others.

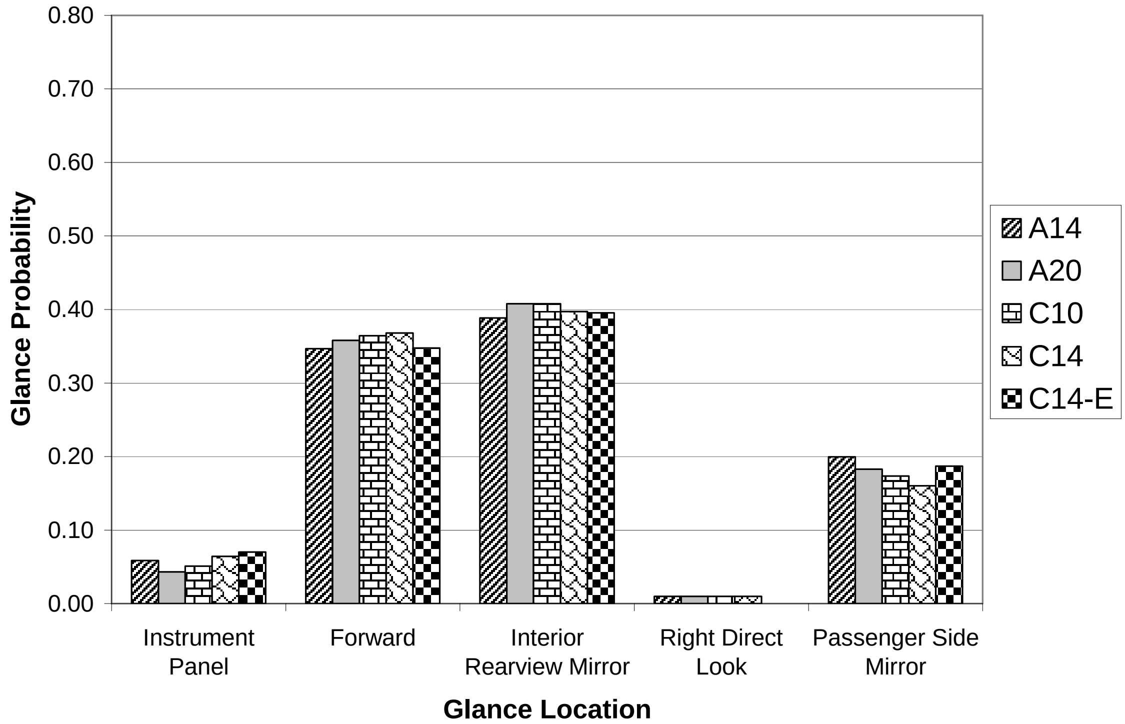


**Figure 77. Glance probabilities for the older subjects as a function of mirror type in the decelerating merge maneuver, passenger side.**

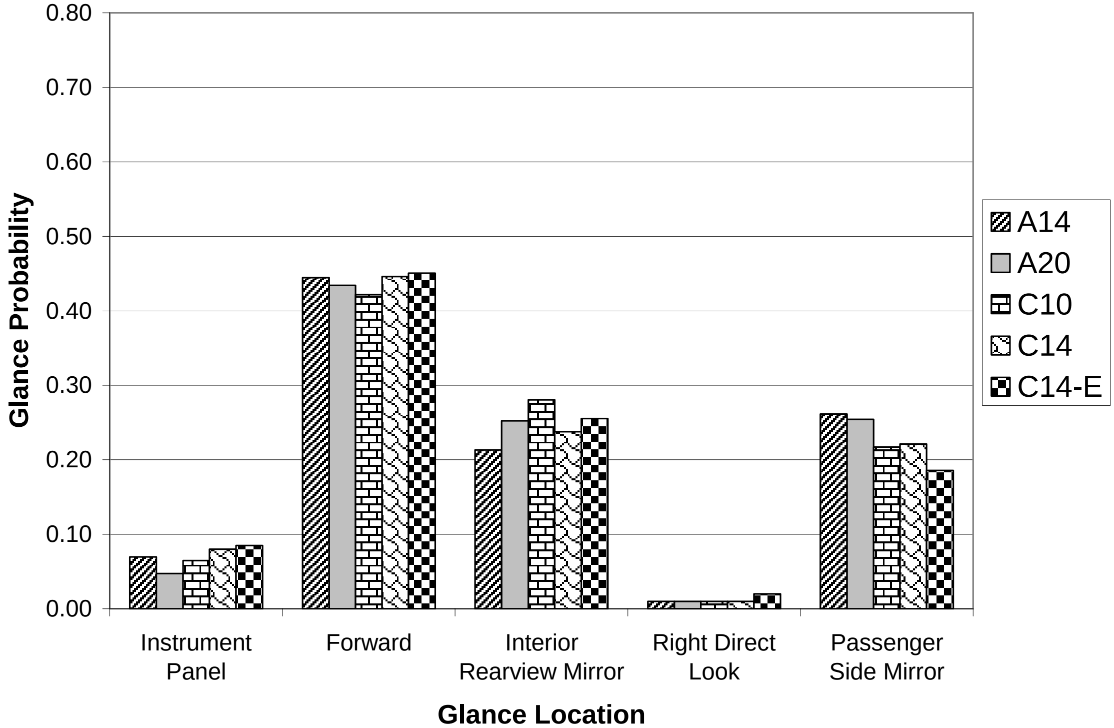


**Figure 78. Glance probabilities for the younger subjects as a function of mirror type in the decelerating merge maneuver, passenger side.**

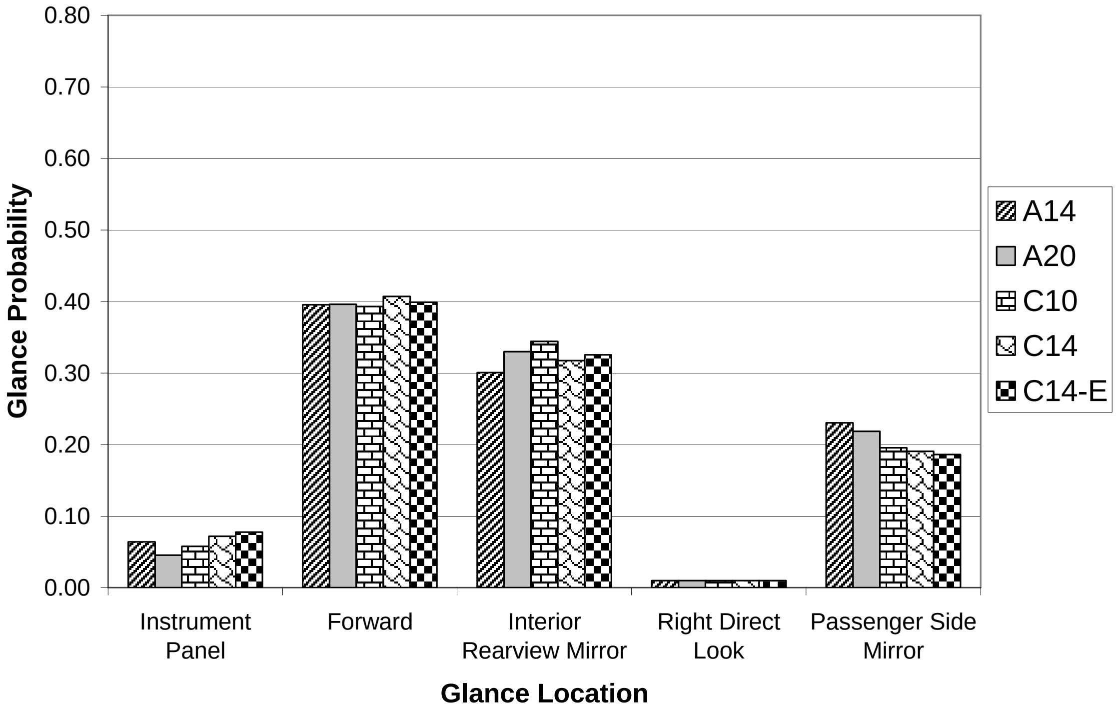


**Figure 79. Glance probabilities for all subjects as a function of mirror type in the decelerating merge maneuver, passenger side.**

Finally, for the accelerating merges on the passenger side (see Figure 53), the eyeglance distributions are shown in Figures 80, 81, and 82. Except for the fact that older subjects tended to use their interior mirror a bit more, differences are quite small. Once again there is a good deal of uniformity in the plots as a function of mirror type. Note specifically however that younger drivers used the forward view at least as much as the older drivers.

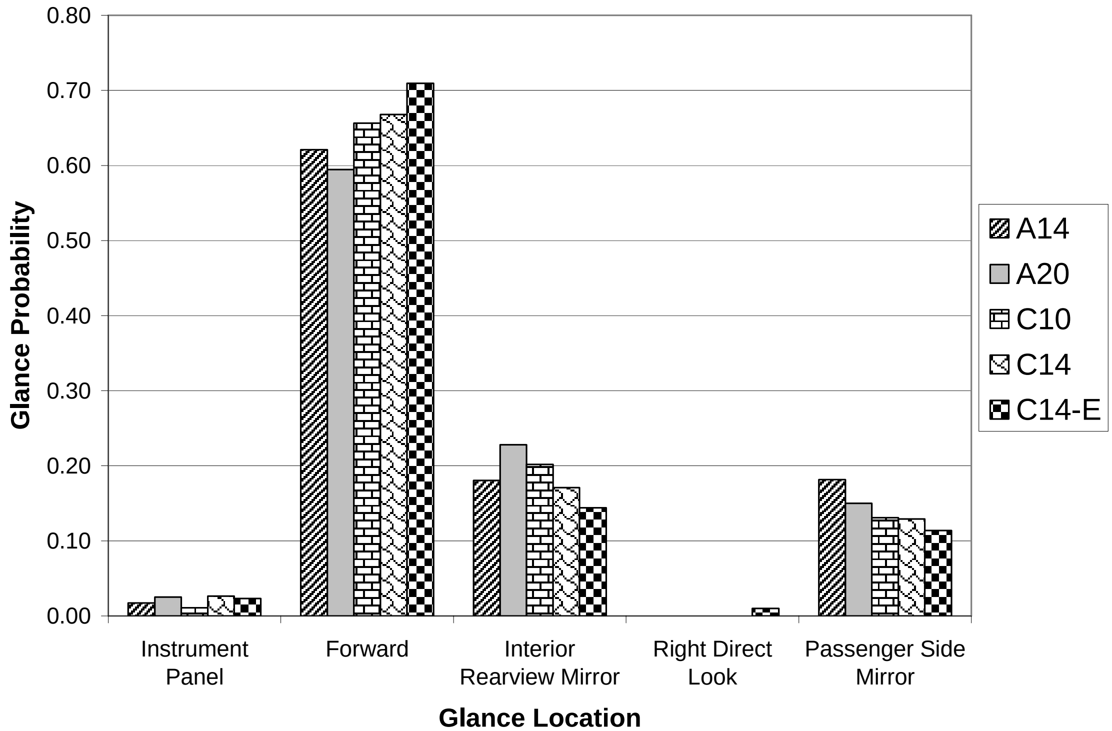


**Figure 80. Glance probabilities for the older subjects as a function of mirror type in the accelerating merge maneuver, passenger side.**

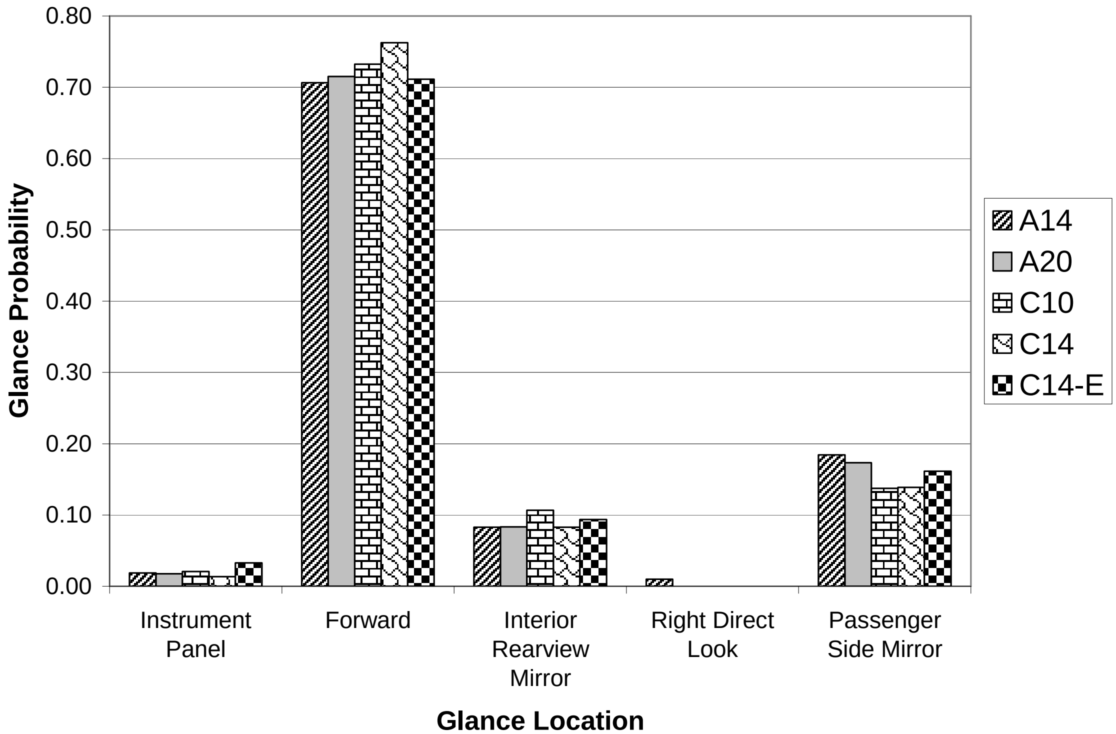


**Figure 81. Glance probabilities for the younger subjects as a function of mirror type in the accelerating merge maneuver, passenger side.**

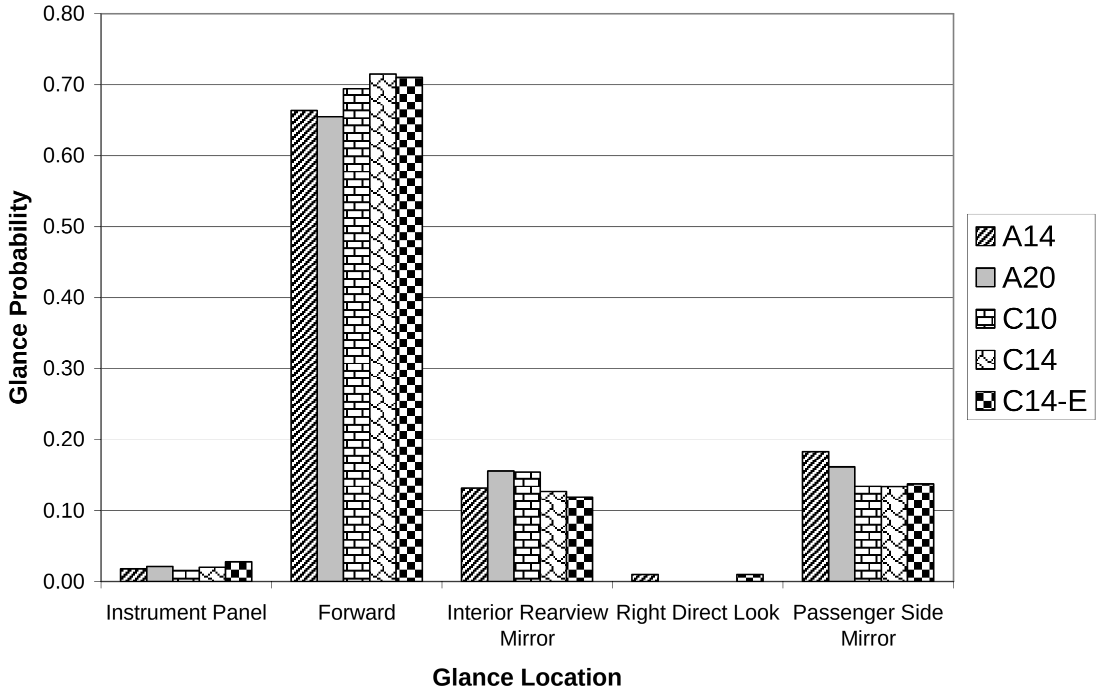


**Figure 82. Glance probabilities for all subjects as a function of mirror type in the accelerating merge maneuver, passenger side.**

## Analyses Associated with the Last-Comfortable-Gap Experiment

In the way of review, this experiment involved having the subject determine the last instant at which it would be comfortable to pull into the adjacent lane (possibly accelerating) in front of a car approaching from the rear (Figures 54 and 55). The subject used a pushbutton mounted on the end of the stalk just behind the right side of the steering wheel (Figure 56) to signal the last comfortable gap. Longitudinal distance between the rear of the subject vehicle and the front of the approaching confederate vehicle was determined at the instant of button press using the DGPS systems installed on the two vehicles. It was this distance that was analyzed. There were eight replications of this task for each driver using each outside rear-view mirror. Recall that subjects did not actually perform the lane change and passing maneuver.

The driver-side results were analyzed using an ANOVA, with the between subjects independent variables of age group and gender, and with the within subjects independent variables of mirror type and event. In this case event represented the specific replication; that is, first through eighth. There were two age groups, two genders, seven mirrors, and of course eight events in the driver-side analysis.

The results of the analysis demonstrated only one significant effect, the age main effect, $F(1,24) = 11.38$, $p = 0.0025$. There were no other significant main effects or interactions. For purposes of completeness it is worth noting that the mirror main effect was not significant, $F(6,142) =$

1.41, $p = 0.214$. Considering that this experiment had substantial statistical power, it is clear that mirror type did not play a major role in last-comfortable-gap estimation.

The age main effect is plotted in Figure 83. As the figure shows, older subjects were much more conservative than younger subjects in their estimations of last comfortable gap. In fact, older subjects estimated gaps that on average were twice as large as those estimated by younger subjects.

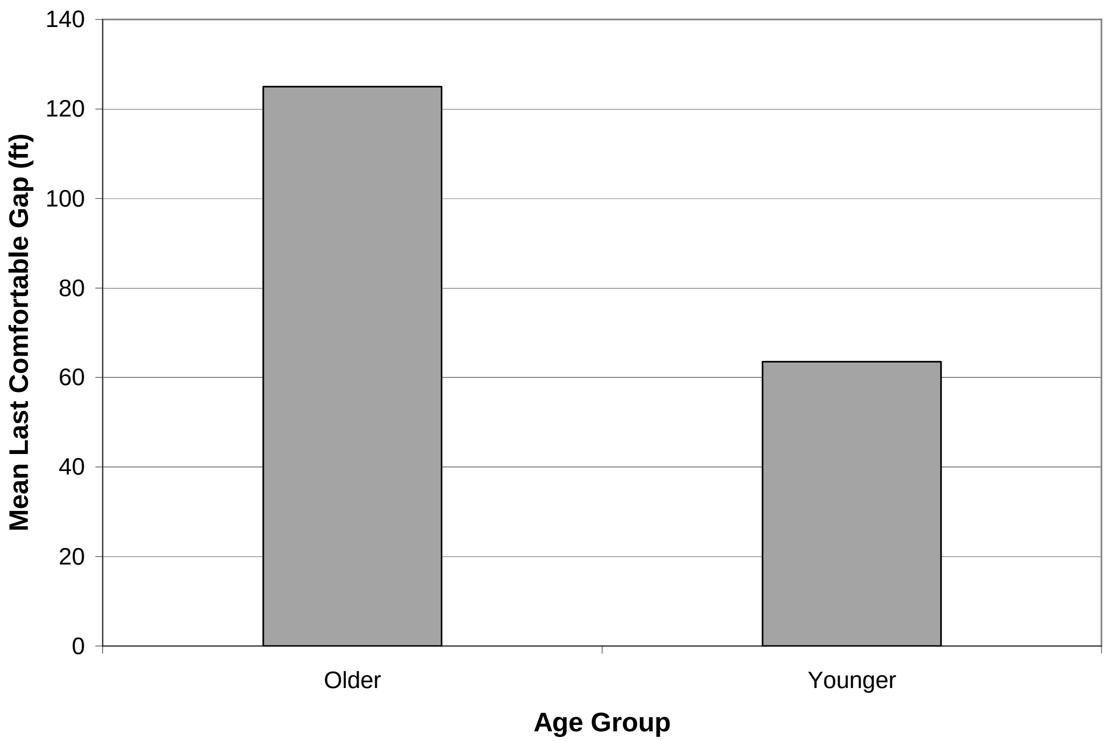


**Figure 83. Mean last comfortable gap as a function of age, driver side.**

Because of the large difference in mean last comfortable gap as a function of age, a further examination of the data was undertaken. Specifically, the mean last comfortable gap for each subject was examined to determine if there were outlier subjects who might have substantially influenced the outcome of the analysis. The results of this examination suggested that there were no outliers. The range for older subjects was 44 to 256 ft (13.4 to 78.0 m) and the range for younger subjects was 23 to 108 ft (7.0 to 32.9 m). In each case the data appeared to have been drawn from a normal distribution.

The passenger-side results were similarly analyzed using an ANOVA, with the between subjects independent variables of age group and gender, and with the within subjects independent variables of mirror type and event. Event again represented the specific replication; that is, first through eighth. Again there were two age groups and, of course, two genders. However, there were five mirrors for the passenger-side analysis.

The results of the analysis demonstrated two significant main effects: the age main effect, F(1,16) = 5.88, *p* = 0.0028 and the event main effect, F(7,112) = 2.51, *p* = 0.0194. There were no other significant main effects or interactions. In regard to the most important independent variable, mirror type, results did not approach significance, F(4,64) = 0.26, *p* = 0.903. Once again, it is clear that mirror type did not play a major role in the outcome of the experiment.

The age main effect for the passenger side is plotted in Figure 84. It shows results similar to the driver-side results in that older subjects were much more conservative than younger subjects in estimating last comfortable gap. Once again, the younger subjects on average selected gaps that were only half as large as those selected by older subjects. To examine this large difference, mean last-comfortable-gap estimations for each subject were computed. The range across older subjects was 67 to 465 ft (20.4 to 141.7 m). However the *second* largest mean was189 ft (57.6 m), suggesting that one of the older subjects could be considered an outlier. In the absence of the subject with the largest mean, the grand mean for last comfortable gap was 127.1 ft (38.7 m) for the remaining older subjects and, in addition, the data appeared to have been drawn from a normal distribution. For the younger subjects the range across subjects was 40 to 131 ft (12.2 to 39.9 m). However, in this case there were no outliers and the data appeared to have been drawn from a normal distribution.

To determine if the outlier subject had undue influence on the domain of significance, that subject's data were eliminated from the data set and an unequal-Ns ANOVA was computed. The results again showed that only the age group and event main effects were significant: Age group F(1,15) = 12.24, *p* = 0.0032; Event F(7,105) = 2.24, *p* = 0.0363. There were no other significant main effects or interactions. Consequently, it is clear that even with the outlier removed, there are no major changes in the outcome of the analysis and the older subjects provided much more conservative estimations of last comfortable gap (127.1 vs. 79.9 ft; 38.7 vs. 24.4 m).

It is important to note once again in these last-comfortable-gap analyses that subjects performing the passenger-side tasks were different from those performing the driver-side tasks. Nevertheless, there are large differences in last comfortable gap on *each* side, further verifying that older subjects wanted much greater distances to pull out and pass.

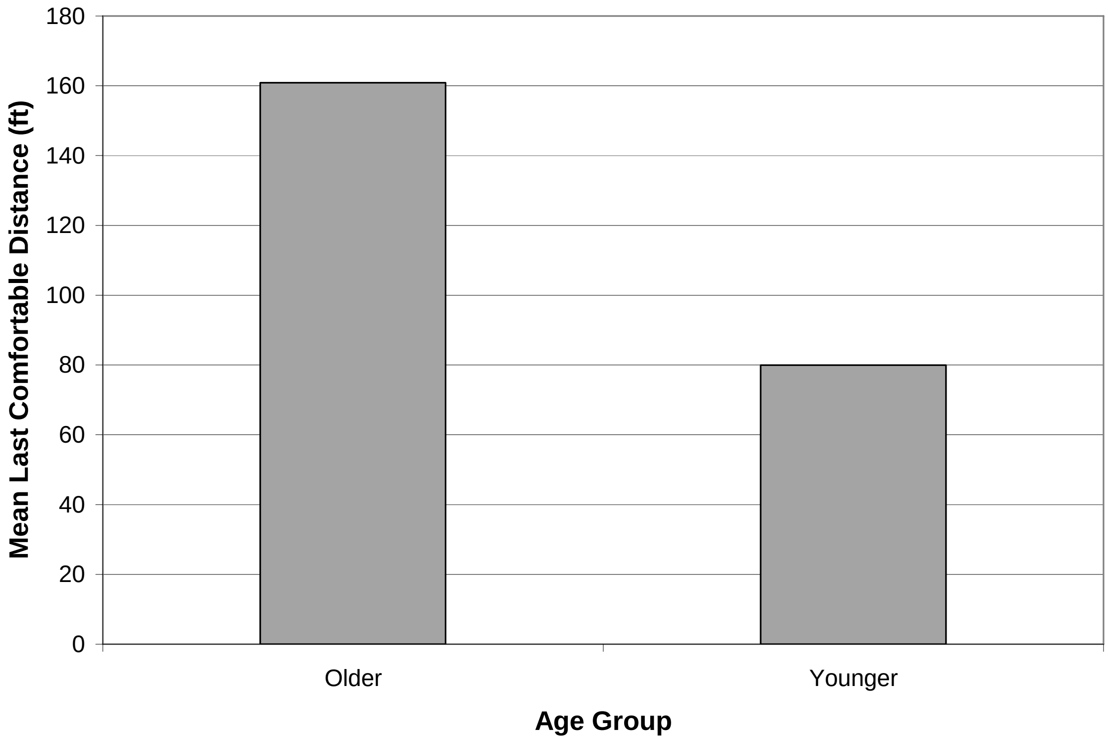


**Figure 84. Mean last comfortable gap as a function of the age, passenger side.**

In regard to event, this main effect is plotted in Figure 85 (using all the data). Means with a common letter do not differ significantly using the SNK test. As can be seen, the only significant difference is between the second replication and the eighth replication. Also, the entire range is quite narrow, with the maximum difference being only 13.6 ft (4.15 m). Consequently, while event exhibits a significant main effect (probably as a result of the statistical power of the experiment), the actual difference between the largest and smallest cut-in distance is relatively small; that is, approximately 10 percent of the average cut-in distance.

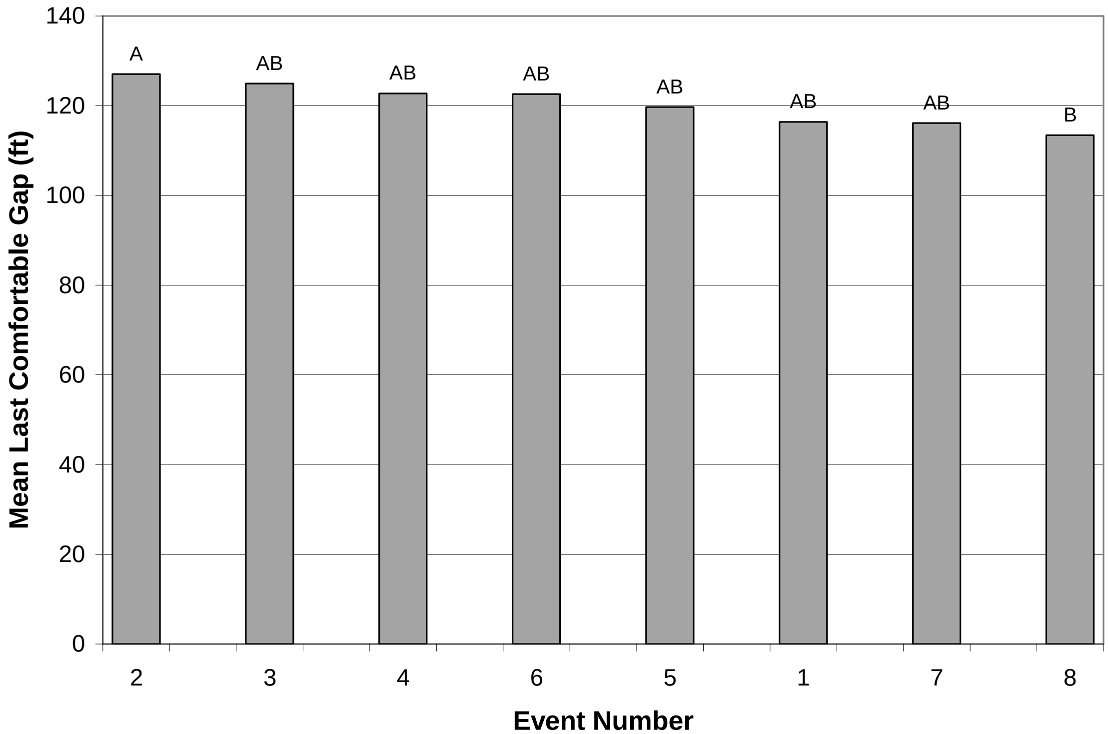


**Figure 85. Mean last comfortable gap as a function of event, passenger Side.**

Eyeglance data for the lastlast-comfortable-gap experiment were analyzed in the same way as the passing/merging tests. In particular, eyeglance data for the 10 s period immediately preceding each button press were used, considering that these data would correspond to the interval during which the subjects were making the decision regarding last comfortable gap. As had been done previously, distributions of eyeglance probabilities were developed for older and younger subjects separately, in an attempt to discern any age related differences. Thereafter, the plots were combined to obtain one grand distribution for each side of the vehicle.

Figure 86 shows the glance location probabilities for the older subjects as a function of mirror type for the driver-side experiment, while Figure 87 shows the glance probabilities for the younger subjects for the driver side. When the figures are compared, they show that older subjects were somewhat more reticent to rely on their driver-side mirrors than younger subjects. Instead, older drivers used the interior rear-view mirror somewhat more, a pattern that had been seen in the passing and merging tests. Considering that their last-comfortable-gap values are larger, it is not surprising that they relied more heavily on their interior mirrors. Clearly, they could view the approaching vehicle (at greater distances) during the decision-making interval using their interior mirror. The interior mirror was, of course, a flat mirror, on which they could supposedly rely. Note however that the F and F-E driver-side mirrors were used somewhat more by the older drivers than were the other mirrors. Here again, it appears that they felt they could rely more on these mirrors, since supposedly the mirrors provided an indication of "true" distance. Note however that younger drivers also used the F-E mirror more than the other driver-side mirrors.

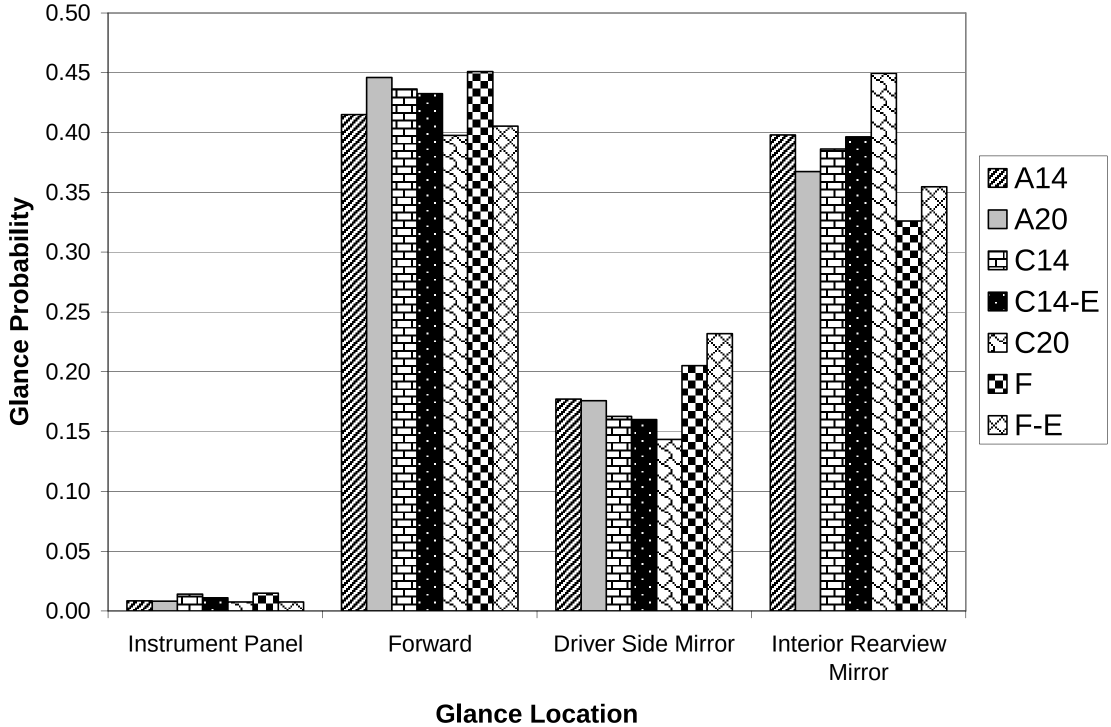


**Figure 86. Glance probabilities for the older subjects as a function of mirror type in the last-comfortable-gaplast comfortable gap experiment, driver side.**

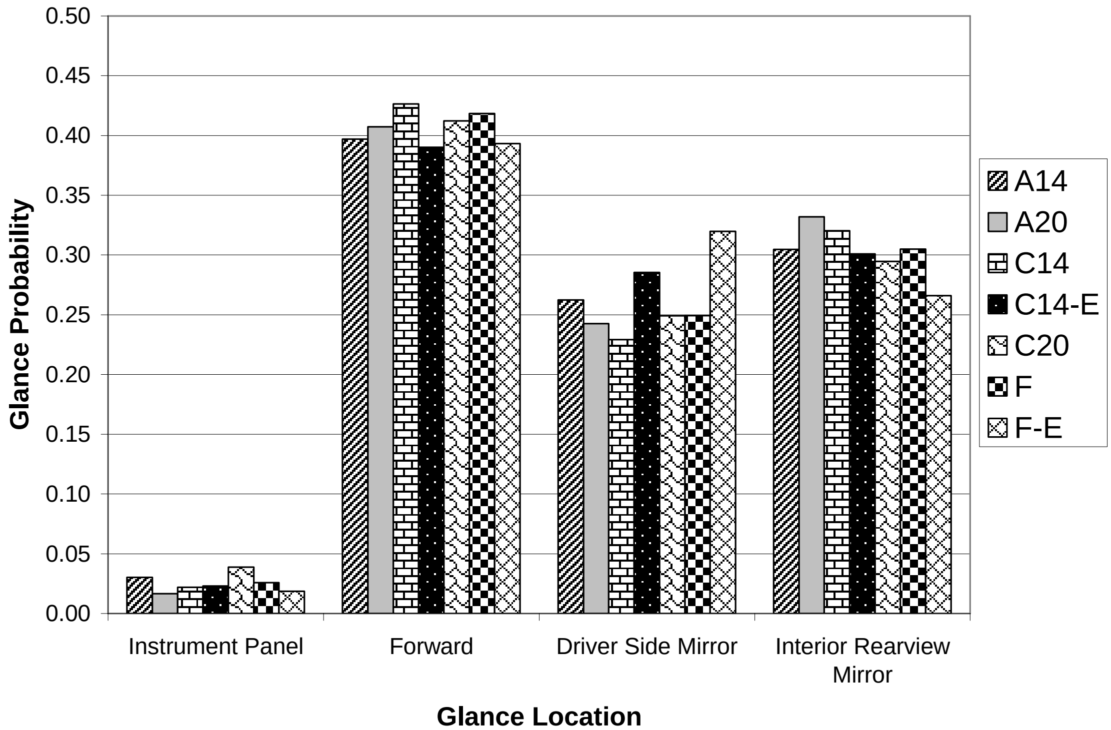


**Figure 87. Glance probabilities for the younger subjects as a function of mirror type in the last-comfortable-gap experiment, driver side.**

When the plots are combined, they show that there is very little difference in the use of the various driver-side mirrors (Figure 88). However, the F-E mirror is used a bit more than the others, probably because it supposedly provided a true size image. In all cases, drivers relied more heavily on their interior mirror than on the driver-side mirrors. Finally, it should be mentioned that none of the subjects took any direct glances to the rear, as expected, for the driver-side experiment.

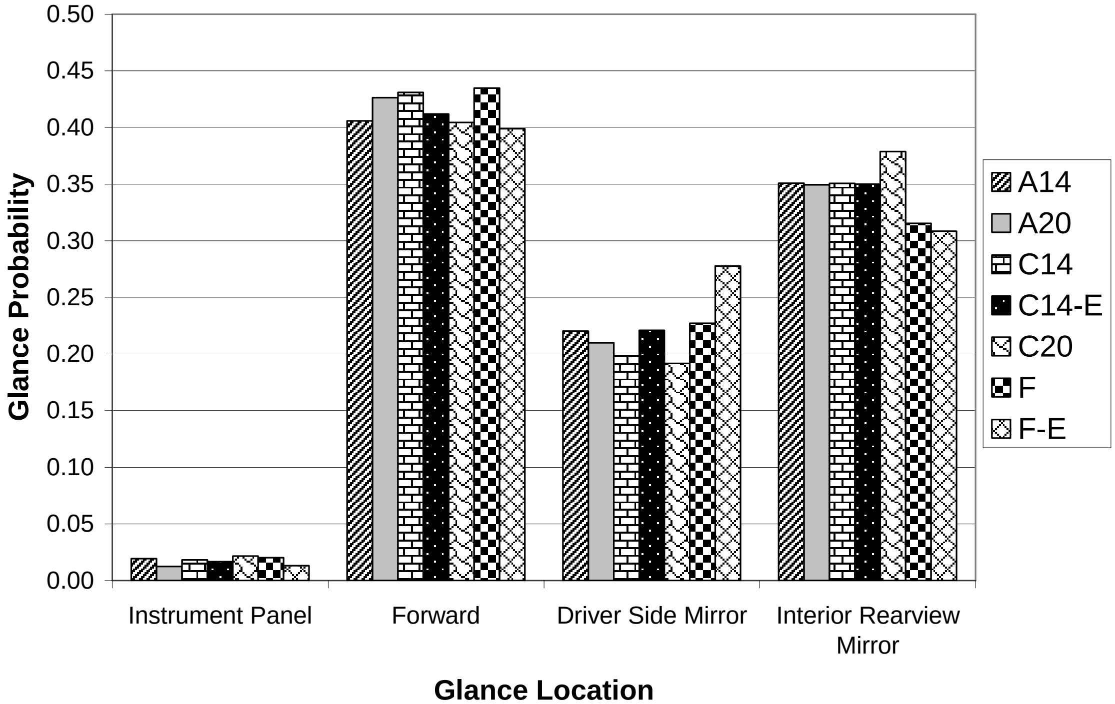


**Figure 88. Glance probabilities for all subjects as a function of mirror type in the last-comfortable-gap experiment, driver side.**

The glance probabilities for the passenger side are shown in Figure 89 for older subjects, Figure 90 for younger subjects, and Figure 91 for all subjects. In comparing Figures 89 and 90, it becomes clear that younger subjects relied quite a bit more on their passenger-side mirror than did older subjects, whereas older subjects relied more heavily on their interior mirror. Figure 91 shows that the differences in use of the various passenger-side mirrors were quite small. It should be noted that none of these mirrors was flat. Also, once again, there were no direct looks to the rear.

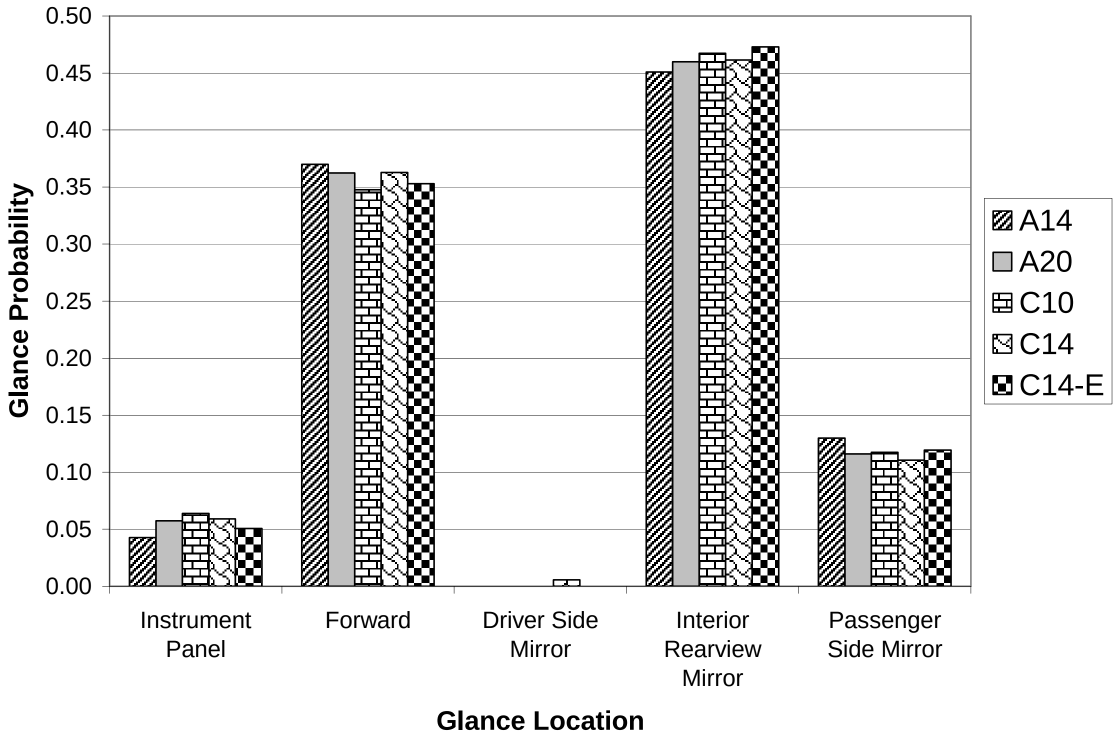


**Figure 89. Glance probabilities for the older subjects as a function of mirror type in the last-comfortable-gap experiment, passenger side.**

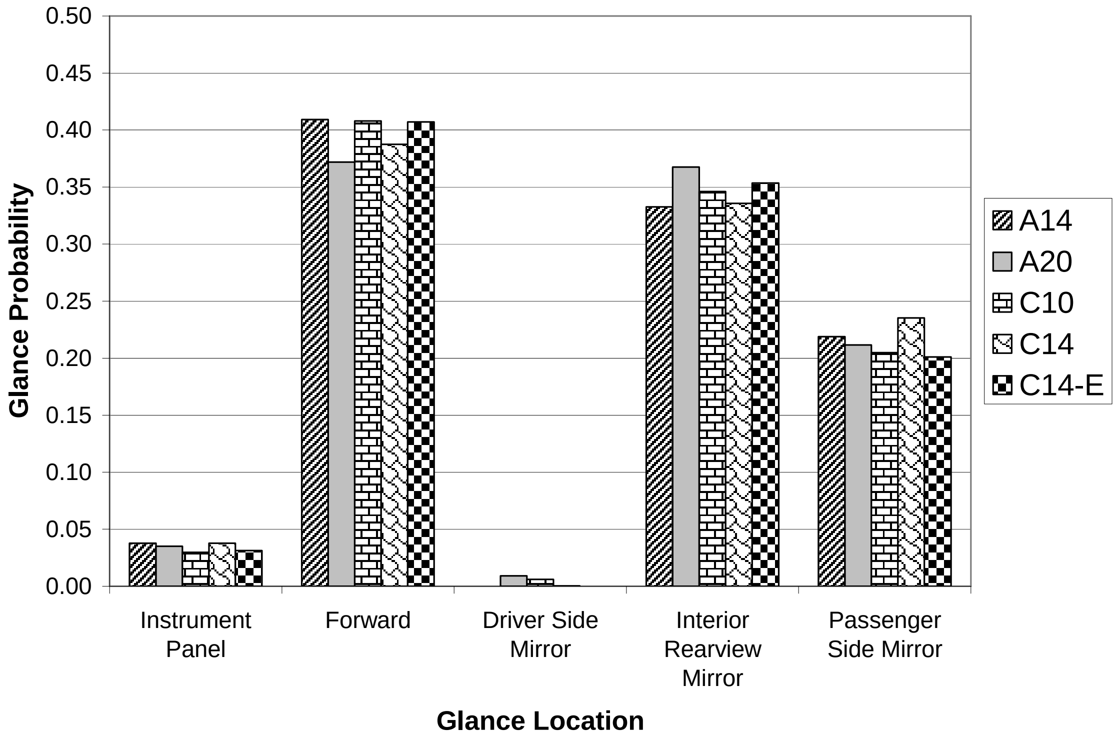


**Figure 90. Glance probabilities for the younger subjects as a function of mirror type in the last-comfortable-gap experiment, passenger side.**

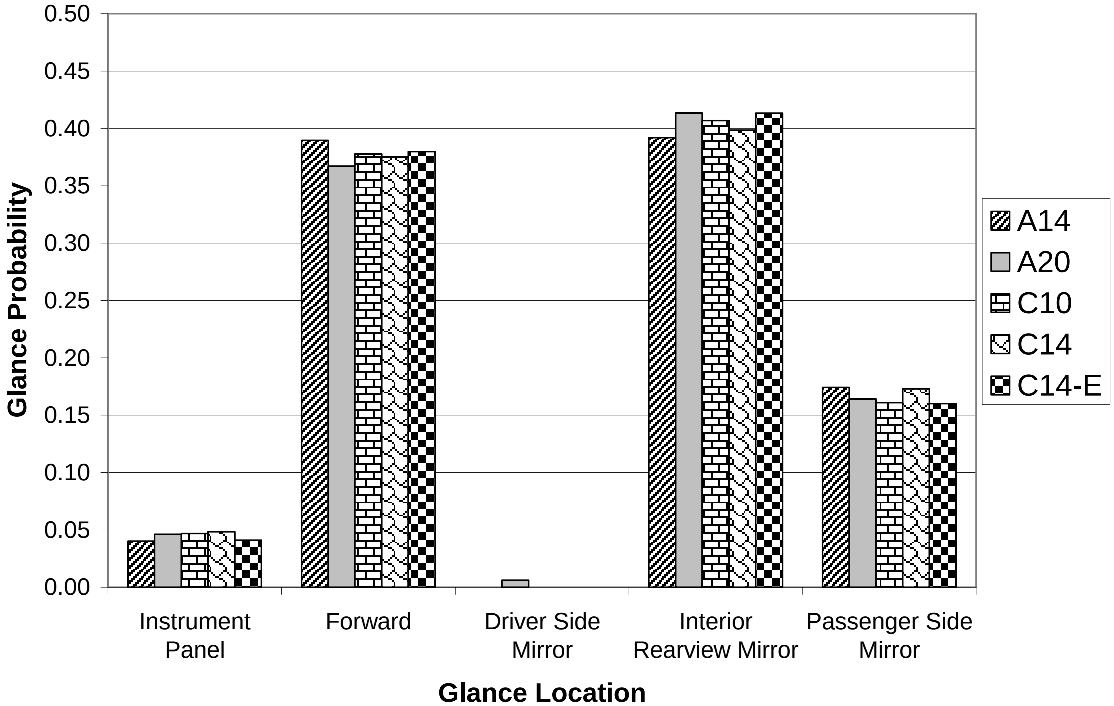


**Figure 91. Glance probabilities for all subjects as a function of mirror type in the last-comfortable-gap experiment, passenger side.**

## Additional Glance Analysis Examining Individual Subject Use of the Outside Mirrors

A question that could be raised involves the degree to which individual subjects used the outside mirror on the side where the maneuver (passing/merging) or estimate (last comfortable gap) was taking place. There is the possibility that many of the subjects did not use their outside mirrors. If so, then the results would be skewed and separate analyses might be needed for those who used their outside mirrors and those who did not use their outside mirrors.

To answer the question of individual subject use of outside mirrors, glance probabilities as a function of side were analyzed on a subject by subject basis. The distributions of glance probabilities were then plotted and information was extracted. Results were combined for the passing and two merging maneuvers. Similarly, they were combined for the last-comfortable-gap estimates. Table 17 summarizes the main characteristics of the subject by subject glance probabilities as a function of relevant side of the vehicle. In all, there were six passing and merging maneuvers for each mirror and there were eight last-comfortable-gap estimates for each mirror.

The results presented in the table show that there is relatively high consistency across subjects. In all four categories shown (driver vs. passenger side; passing/merging vs. last comfortable gap), approximately 90 percent of glance probabilities fell within a confined range, suggesting that subjects reacted visually in much the same way. The conclusion that must be drawn is that the overwhelming majority of subjects used the corresponding outside mirror at least occasionally, if not more often.

**Table 17. Ranges of outside mirror glance probabilities for the subjects in the driver-side and passenger-side experiments.**

| | Driver-Side Mirror Use Probability | Passenger-Side Mirror Use Probability |
|---|---|---|
| Merging and Passing | 89 percent of subjects had glance probabilities between 0.13 and 0.34; 100 percent had glance probabilities of 0.07 or greater; Mean glance prob. = 0.24 Std. dev. of glance prob. = 0.08 | 95 percent of subjects had glance probabilities between 0.06 and 0.24; 100 percent had glance probabilities of 0.06 or greater; Mean glance prob. = 0.17 Std. dev. of glance prob. = 0.06 |
| Last Comfortable Gap | 88.5 percent of subjects had glance probabilities between 0.05 and 0.31; 96.2 percent had glance probabilities of 0.05 or greater; Mean glance prob. = 0.22 Std. dev. of glance prob. = 0.12 | 90 percent of subjects had glance probabilities between 0.04 and 0.28; 95 percent had glance probabilities of 0.04 or greater; Mean glance prob. = 0.17 Std. dev. of glance prob. = 0.11 |

### Opinion Data Analysis

As previously indicated, opinion data were gathered at the end of each subject's participation for each given mirror. This was done so that the subject would have the benefit of using the mirror to the maximum extent that the experiment allowed. There were 6 ratings taken for each mirror and, in addition, subjects could fill in comments at the end of the rating form if they wished to do so. Two of the ratings involved the combined use of the given side mirror with the inside rear-view mirror, and 4 involved the side mirror itself. The scales are shown in Appendix B of this report.

Subjects were instructed to circle one of the 9 vertical delineators for each scale, or alternatively, the horizontal line between delineators, if they felt their ratings should fall between two consecutive delineators. Consequently, there were 17 possible rating positions for each scale. For purposes of statistical analysis after data had been gathered, the first delineator on the left was given a value of 1, the second was given a value of 2, and so on. Thus, the delineator on the right end of the scale was given a value of 9. In those cases where the subject rated between two consecutive delineators, an incremental value of 0.5 was used. For example, if the subject rated between the fourth and fifth delineator, a value of 4.5 was ascribed to the rating.

Note that a value of 5 would occur for the center vertical delineator, and that this value corresponded to a "moderate" rating. Ratings to the right of center (which would be greater than 5) could then generally be considered as favorable and values to the left of center (which would be less than 5) could generally be considered as unfavorable (See Appendix B). However, for ratings of distortion, a 5 would correspond to moderate distortion. Similarly, for ratings of uneasiness, a 5 would correspond to moderate uneasiness. Consequently values higher than 5 would be considered desirable. For example, a value of 7 would be more acceptable, since it would correspond to mild distortion or slight uneasiness.

The ratings for each mirror on each side of the vehicle were analyzed statistically to determine if significant differences were present among the mirrors. The main technique used was ANOVA, with independent variables of age group, gender, and Mirror.

The driver side ANOVA for the "coordination" ratings demonstrated a main effect of mirror $F(6,144) = 7.1$, $p < 0.0001$, and an interaction of age group and gender $F(1,24) = 5.8$, $p = 0.024$. Figure 92 shows the plot of mean ratings as a function of mirror. In this and the following plots, means with a common letter are not significantly different using the SNK test. The plot shows that the two flat mirrors received higher ratings than any of the conventional size curved mirrors, including the two aspherics. However, all of the mirrors received ratings above the 5 level.

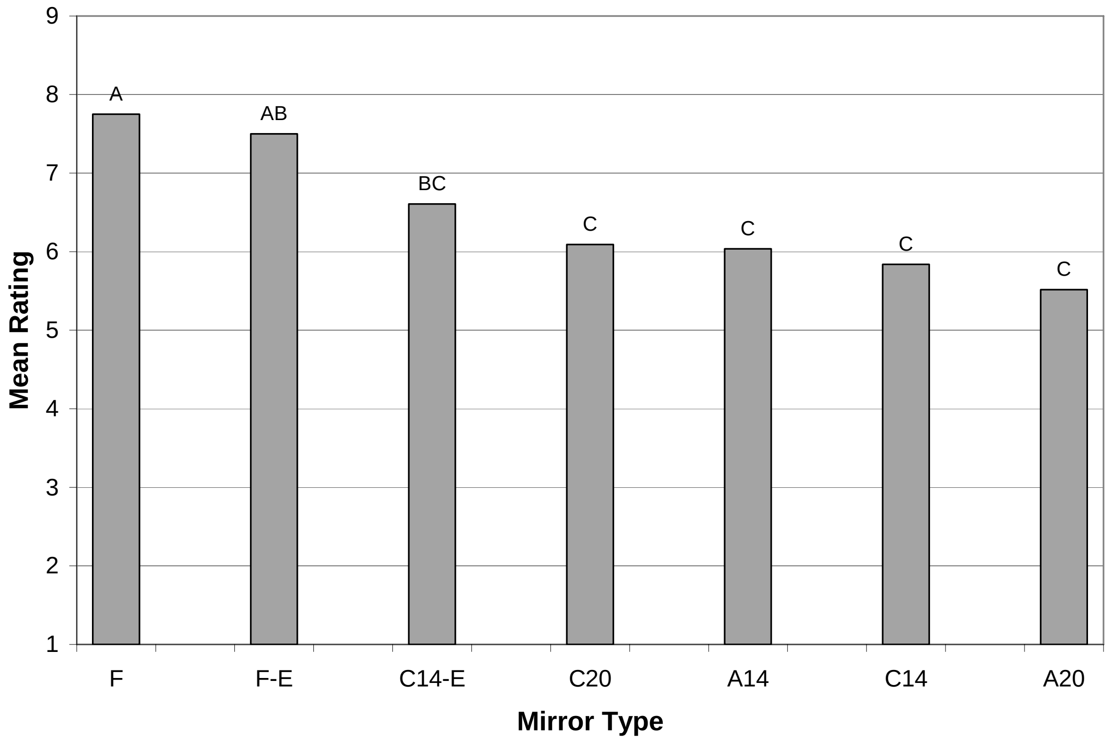


**Figure 92. Mean ratings for coordination as a function of mirror type, driver side.**

The interaction effect of age and gender is shown in Figure 93. This plot shows that younger females rated higher on average than younger males, while older females rated lower on average than older males.

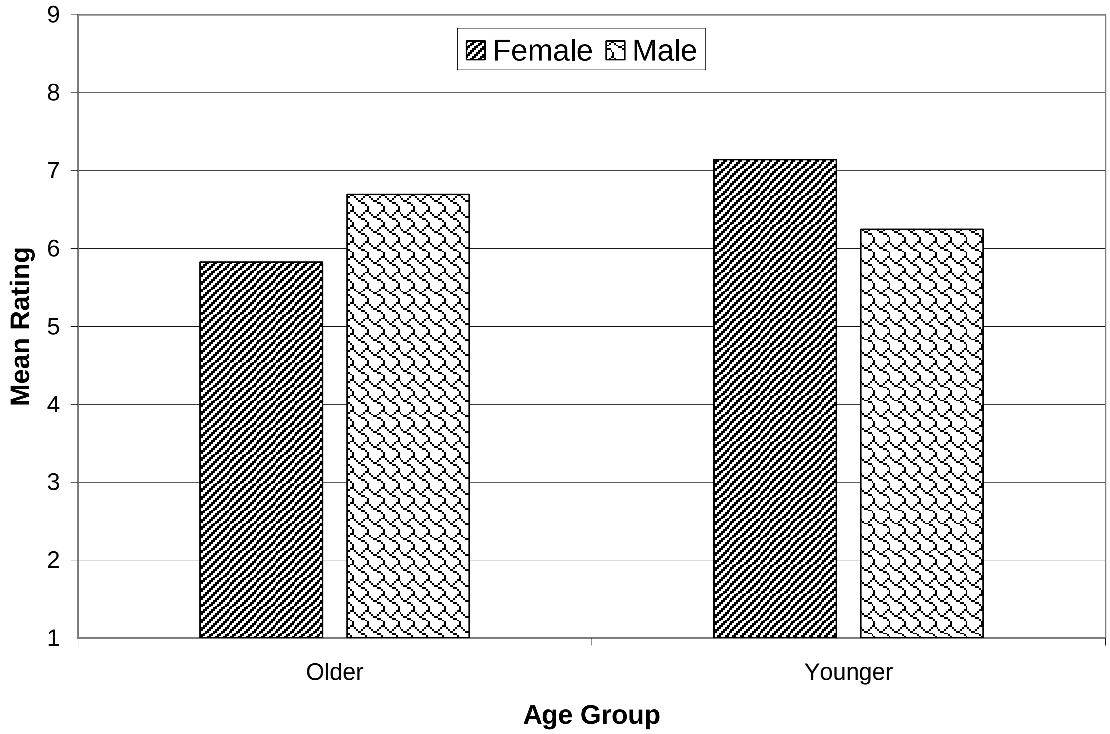


**Figure 93. Mean ratings for coordination as a function of age and gender, driver side.**

The ratings for "Speed and Distance Estimation" similarly demonstrated a significant mirror main effect $F(6,144) = 12.18$, $p < 0.0001$ and a significant age by gender interaction $F(1,24) = 9.3$, $p = 0.0055$. The mirror main effect is plotted in Figure 94. It shows that the two flat mirrors differed significantly from three of the five curved mirrors, including the two aspherics. Also, the elongated flat mirror differed significantly from all of the curved mirrors. The two aspherics and the C14 received mean ratings close to the 5 level.

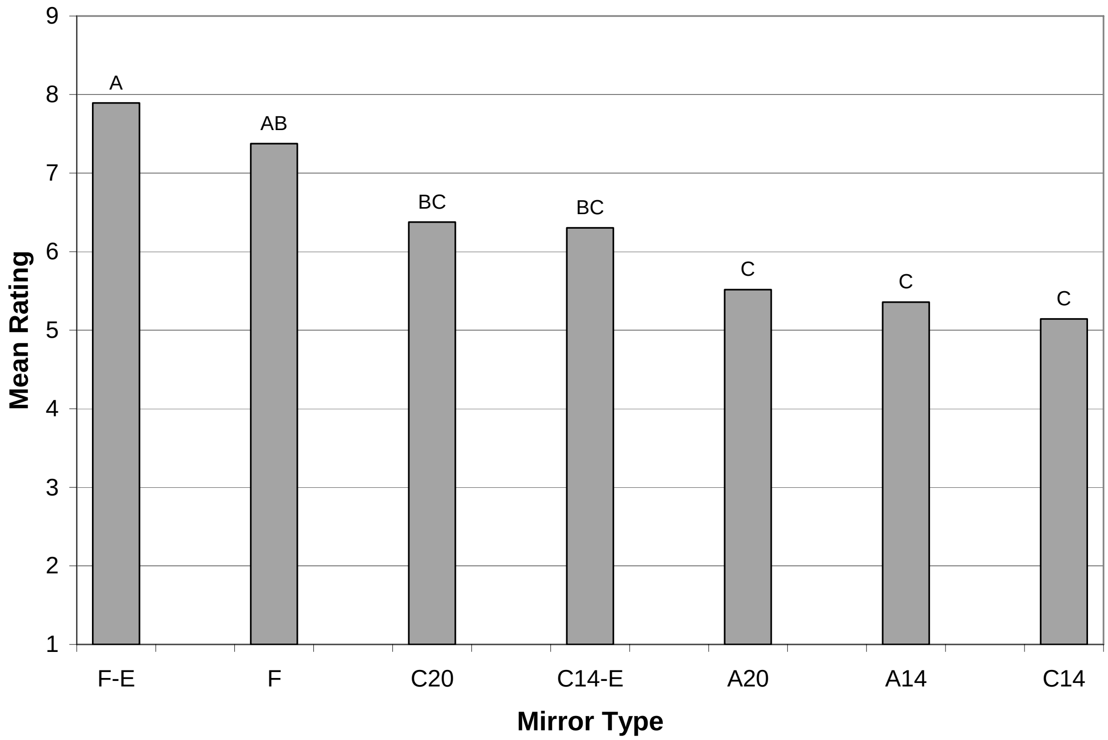


**Figure 94. Mean ratings for speed and distance estimation as a function of mirror type, driver side.**

The age by gender interaction showed the same trend for speed and distance estimation as it did for Coordination, as shown in Figure 95. Younger females rated the mirrors higher than younger males, and older females rated them lower than older males.

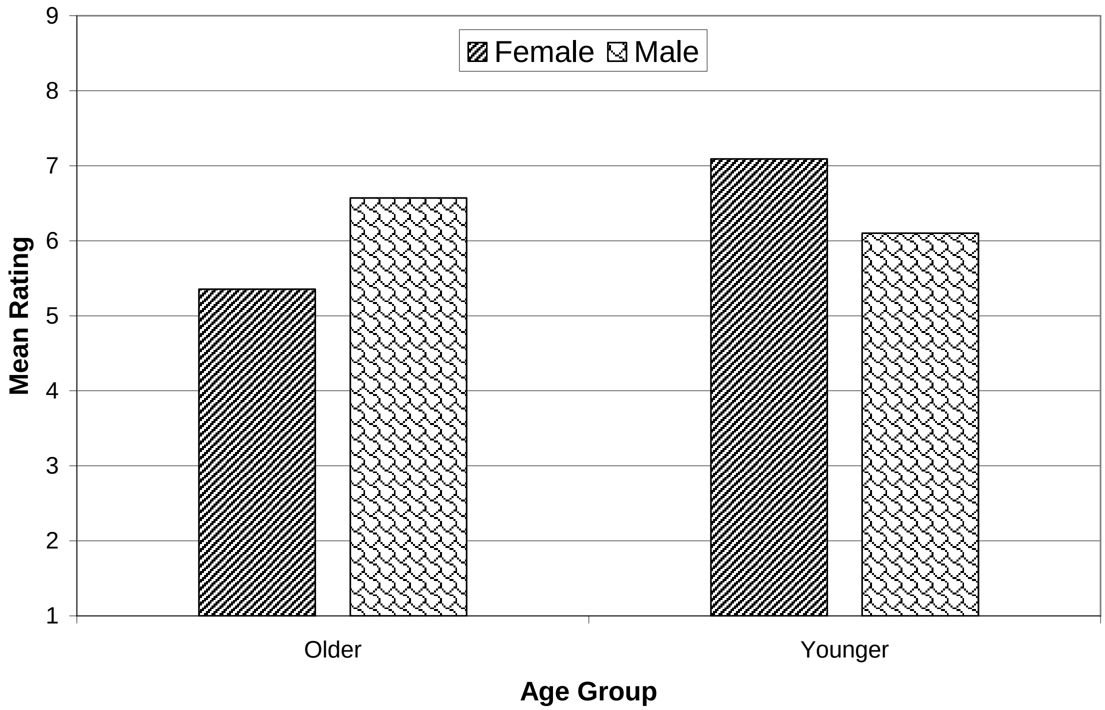


**Figure 95. Mean ratings for speed and distance estimation as a function of age and gender, driver side.**

For the Field-of-viewfield-of-view ratings on the driver side, only the age group by mirror interaction was significant $F(6,144) = 2.27$, $p = 0.0405$. This interaction is plotted in Figure 96. The results are not especially helpful in terms of comparisons. However, it might be said that younger drivers gave higher ratings to the aspherics (A14 and A20) and to the elongated convex mirror (C14-E) than older drivers. This might indicate greater receptiveness to newer or alternative mirror types.

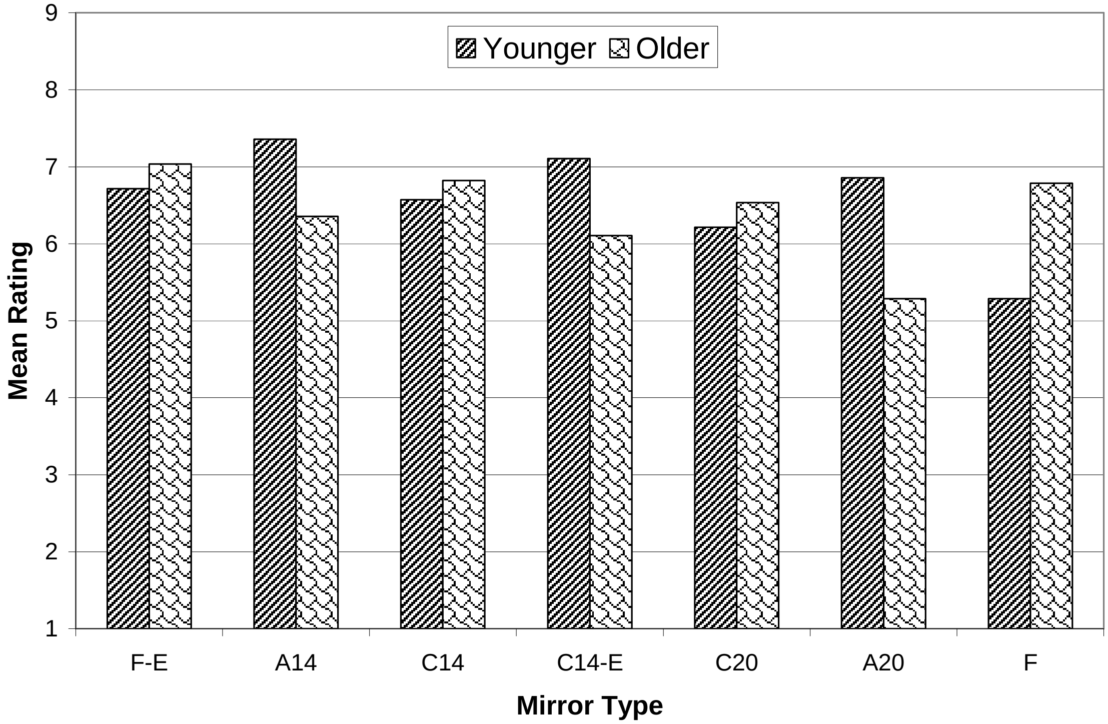


**Figure 96. Mean ratings for field-of-view as a function of age and mirror type, driver side.**

For the Distortion ratings on the driver side, only the main effect of mirror was significant $F(6,144) = 17.91$, $p < 0.0001$. This main effect is plotted in Figure 97. As the figure shows, the two flat mirrors differed significantly from all others in terms of distortion in that they received the highest (most favorable or least distortion) ratings. Also, the A20 was rated significantly lower than the C20 or C14E mirrors, and the A20 received a rating slightly below 5. It should be remembered that the A20 had the largest aspheric region. This may have played a role in the rating.

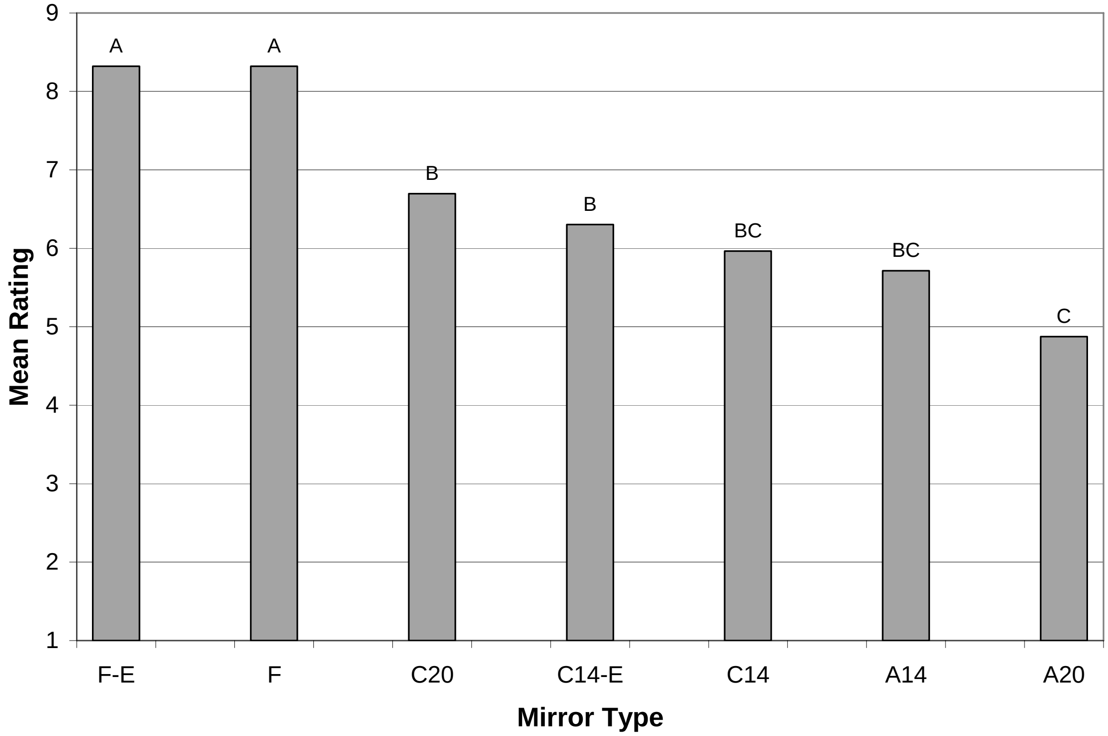


**Figure 97. Mean ratings for distortion as a function of mirror type, driver side. Note that higher values indicate less rated distortion.**

For the Uneasiness ratings on the driver side, again, only the main effect of mirror was significant $F(6,144) = 7.25$, $p < 0.0001$. This main effect is plotted in Figure 98. The figure shows that the two flat mirrors differed significantly from the two aspherics and the C14 convex mirror.

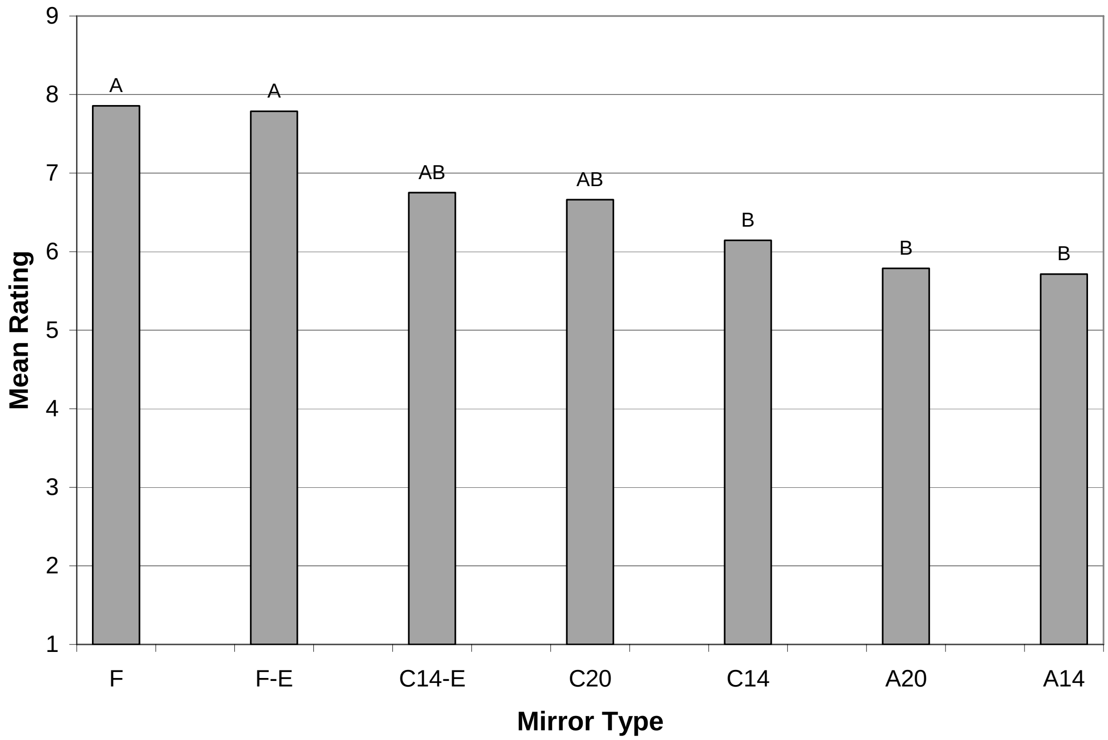


**Figure 98. Mean ratings for uneasiness as a function of mirror type, driver side. Note that higher values indicate less rated uneasiness.**

In regard to comfort level, again, only the main effect of mirror was significant $F(6,144) = 6.93$, $p < 0.0001$. The results, plotted in Figure 99, show that the two flat mirrors produced significantly greater comfort than did four of the five curved mirrors, including the two aspherics. Note that the two aspherics are close to a mean rating of 5.

The wording associated with the comfort level scale is important. It was "I would feel comfortable using this outside mirror on my vehicle." Consequently, comfort level is an indication of receptiveness. Note that a rating of 5 would correspond to moderate receptiveness.

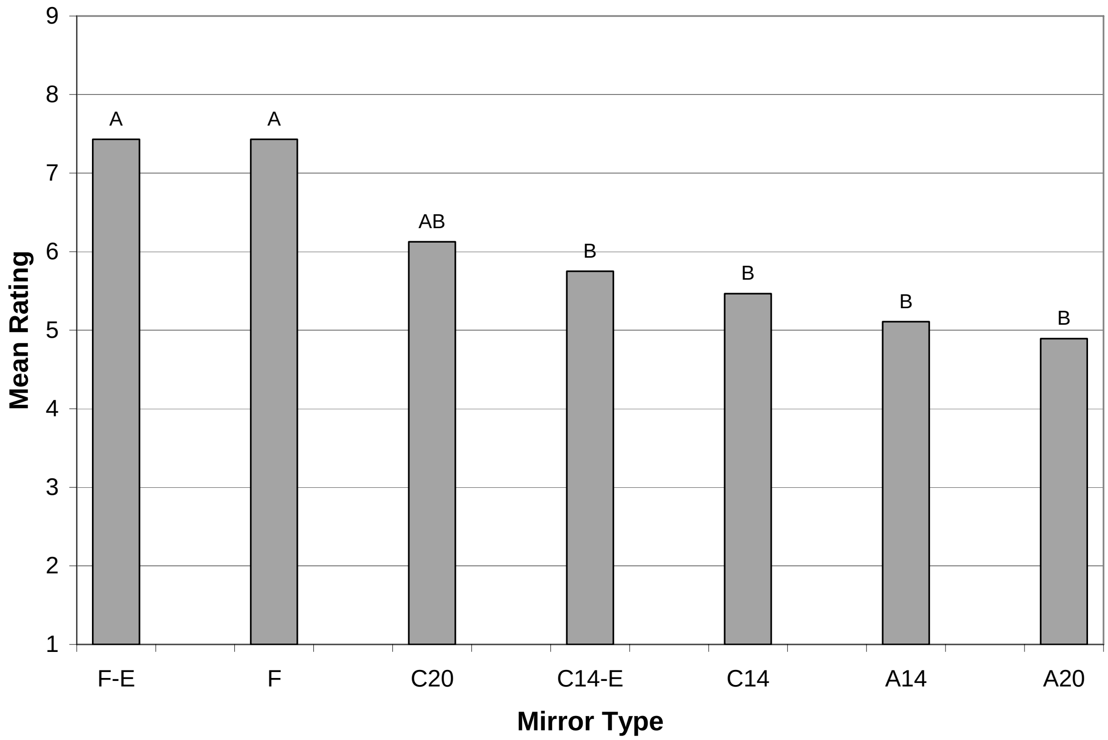


**Figure 99. Mean ratings for comfort level as a function of mirror type, driver side.**

In regard to the passenger-side ratings, only five mirrors were rated, as previously described. Data for each rating scale were once again examined using individual ANOVAs. None of the mirrors tested on the passenger side was flat, suggesting that the domain of significance should be smaller.

The passenger-side ANOVA for the coordination ratings revealed no significant differences. Most importantly, the mirror effect was not significant $F(4,64) = 1.57$, $p = 0.192$. Similarly, the ANOVA for speed and distance estimation ratings revealed no significant differences. In this case the mirror main effect was again not significant with $F(4,64) = 0.97$, $p = 0.431$.

The passenger-side ANOVA for "field-of-view" ratings demonstrated a significant main effect of age group $F(1,16) = 4.56$, $p = 0.0485$. No other main effects or interactions were significant. In particular, the mirror effect was not significant $F(4,64) = 0.86$, $p = 0.493$.

The age main effect is plotted in Figure 100. It shows that younger subjects rated field-of-view of the mirrors as a group substantially higher than the older subjects did.

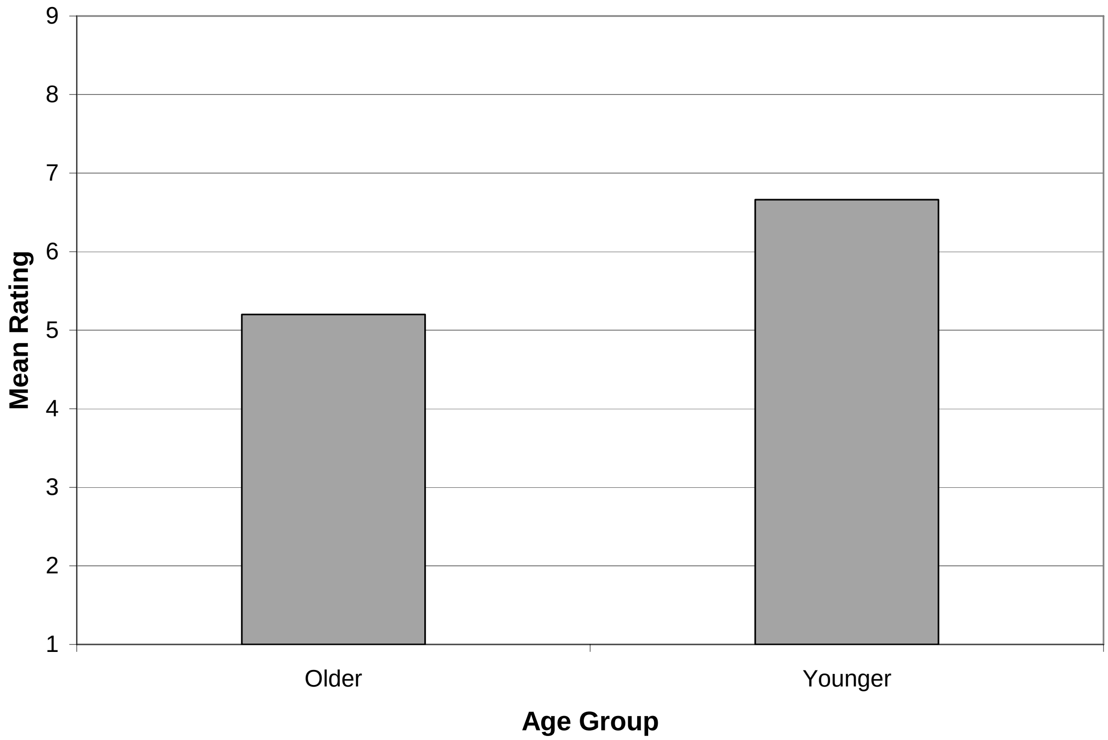


**Figure 100. Mean ratings for field-of-viewfield-of-view as a function of age, passenger side.**

The ANOVA for distortion on the passenger side demonstrated significance for the gender $F(1,16) = 5.67$, $p = 0.030$ and mirror $F(4,64) = 4.96$, $p = 0.0015$ main effects, and the age group by gender interaction $F(1,16) = 7.58$, $p = 0.0141$. The age group main effect and the two other interactions were not significant. Figure 101 shows the main effect of gender in which males provided higher ratings, indicating less distortion. The interaction of gender with age (Figure 102) shows clearly that it was the older females who had the most trouble with distortion. They provided ratings that averaged to 4.32, which was lower than the other three age/gender groupings.

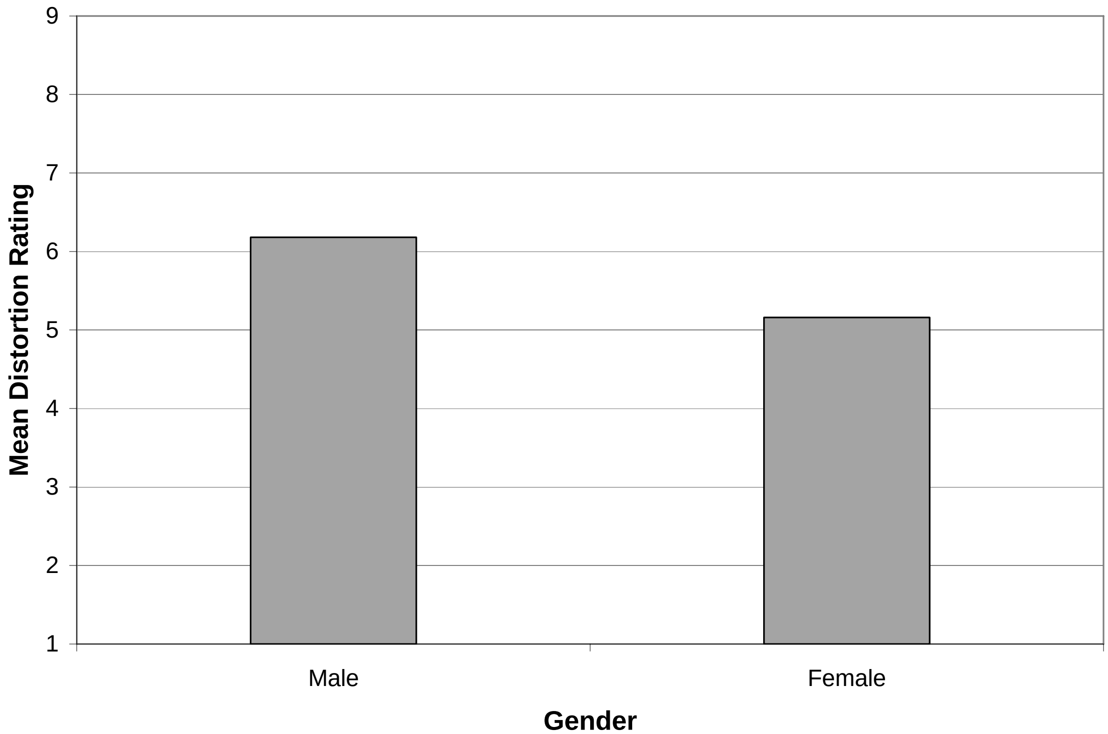


**Figure 101. Mean ratings for distortion as a function of gender, passenger side. Note that higher values indicate less rated distortion.**

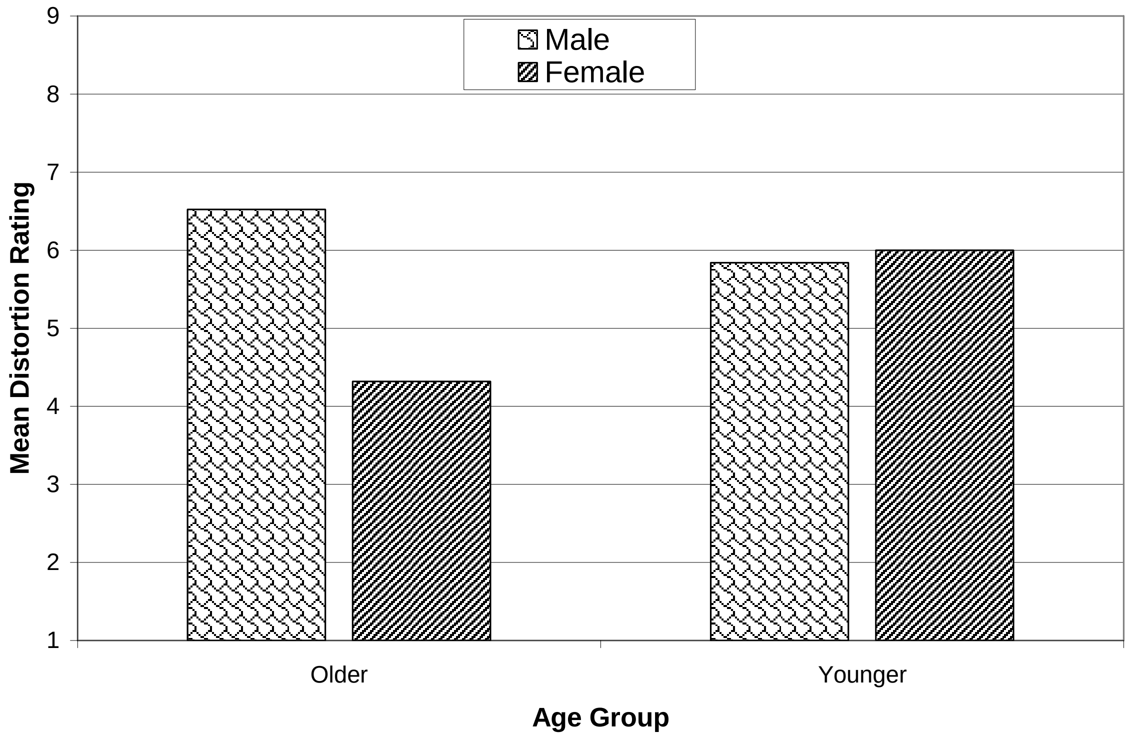


**Figure 102. Mean ratings for distortion as a function of age and gender, passenger side. Note that higher values indicate less rated distortion.**

The main effect of mirror on the distortion ratings is plotted in Figure 103. The plot shows that the C14 mirror was rated as having significantly less distortion than the C10 and the two aspherics. Note that the C14 mirror is in common use today. In addition, the C14-E was rated as having significantly less distortion than the A20.

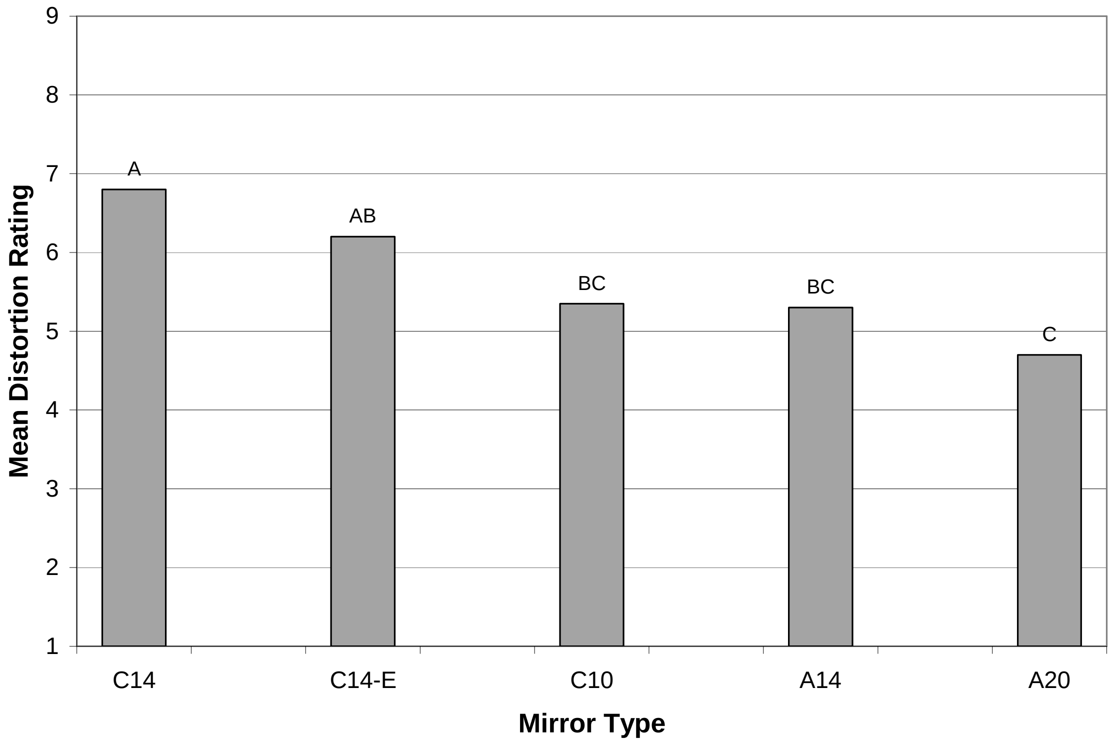


**Figure 103. Mean ratings for distortion as a function of mirror, passenger side. Note that higher values indicate less rated distortion.**

The passenger-side ANOVA for the uneasiness ratings revealed no significant differences. However, the mirror effect, although not significant was not too far from it with $F(4,64) = 2.23$, $p = 0.0759$. Considering that future research might be done, the ratings for uneasiness were plotted as a function of mirror type (Figure 104). Surprisingly, the post hoc SNK test provided significant differences ($\alpha = 0.05$). These were checked using the Tukey HSD test which showed significant differences that were identical to the SNK test. The results of these tests indicate that the C14 mirror had less rated uneasiness than the A20.

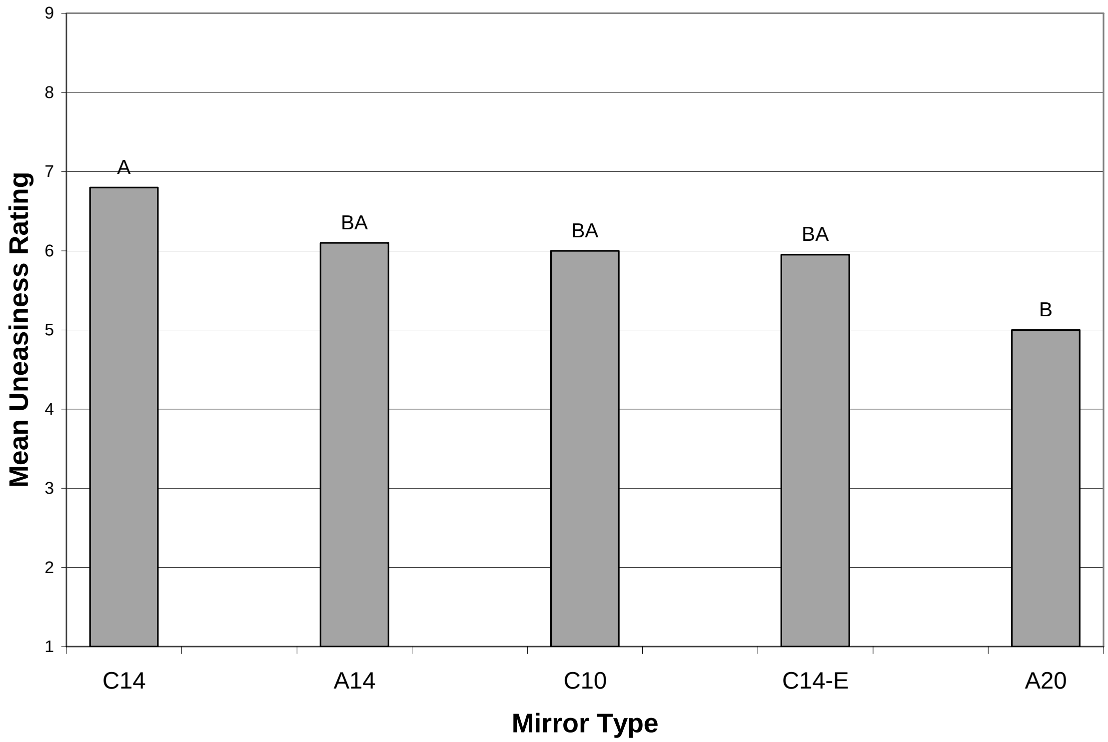


**Figure 104. Mean ratings for Uneasiness as a function of mirror, passenger side. Note that these results were not significant in the ANOVA, *p* = 0.0759, but indicated significant differences in post hoc tests (see text). Note also that higher values indicate less rated uneasiness.**

Finally, the passenger-side ANOVA for comfort level demonstrated a significant main effect of mirror $F(4,64) = 4.23$, $p = 0.0042$. None of the other main effects or interactions was significant. The mirror main effect is plotted in Figure 105. The figure shows that the C14 mirror produced ratings indicating a higher comfort level than either the C10 or A20 mirrors. Note specifically that the A20 mirror received a mean rating value of 4.3.

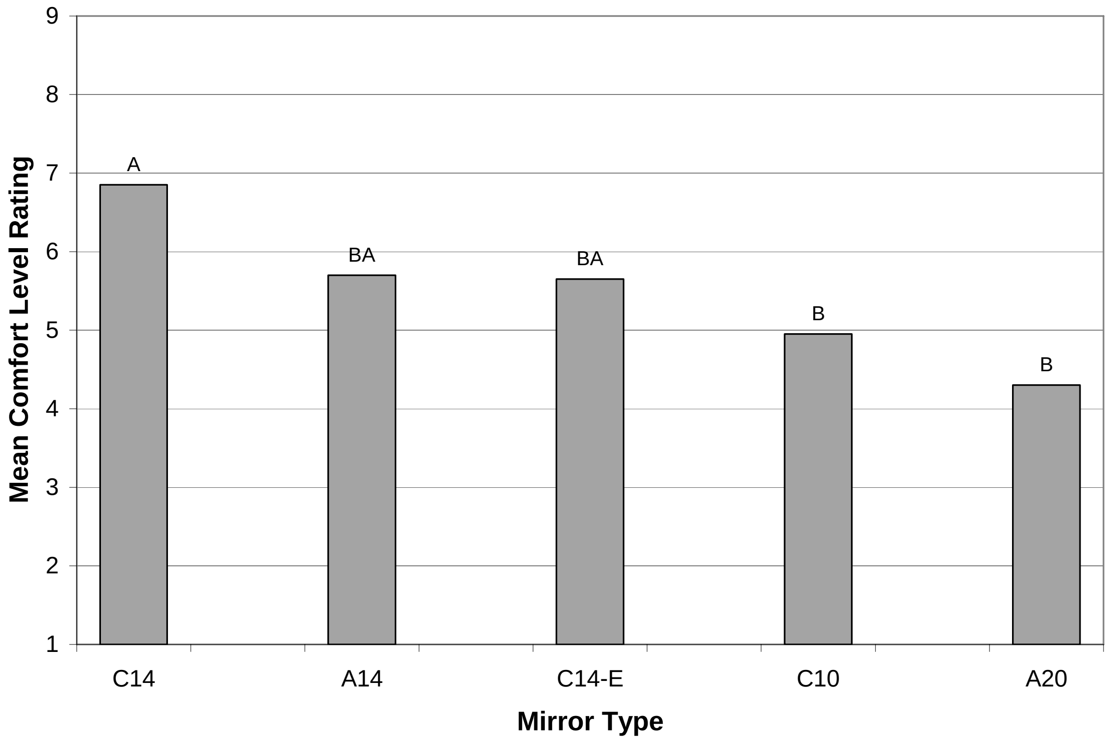


**Figure 105. Mean ratings for comfort level as a function of mirror, passenger side.**

As mentioned, subjects could enter their own comments at the end of the rating form for each mirror, if they wished to do so. These comments were a result of their total experience with the given mirror. The comments were analyzed by the experimenters, who used yet another rating scale to judge each comment in regard to whether the comment was positive or negative, and the degree to which it was positive or negative. Three experimenters participated. The experimenters' rating scale had nine vertical delineators with descriptors of *extremely, very, moderately*, and *somewhat positive* to the right of center and *extremely, very, moderately*, and *somewhat negative* to the left of center in mirror image fashion. The center descriptor was *neutral*. The experimenters used numerical values from 1 to 9 for their ratings, with 5 corresponding to the neutral rating, with 1 corresponding to the left end (extremely unfavorable) rating, and with 9 corresponding to the right end (extremely favorable) rating. The remaining ratings were in numerical order from left to right. Each experimenter independently provided a rating for each comment given by each subject. There was no discussion among the raters during the rating process. The values for the three experimenters were then averaged for each comment.

In many cases the subject used more than one sentence or more than one clause to describe his or her impressions of a given mirror. If so, the portions were separated prior to rating and the portions were rated individually. This was done so that each impression could be included in the ratings. For example, a subject might have indicated that the field of coverage was good, but that the mirror caused some uneasiness. The two impressions were then rated separately so that both the first comment, which would have received a positive rating, and the second comment, which would have received a negative rating, could be taken into account.

The comment ratings, which, as indicated, were averaged for the three experimenters, were then analyzed by a one-way unequal Ns analysis of variance with mirror as the sole independent variable. There was no analysis by subject. Each subject had an equal opportunity to comment on each mirror, and all did make comments. However, there were mirrors for which certain subjects did not provide any comments. Thus, the comments that were given were simply pooled by mirror and then analyzed. On the driver side, the number of rated comments ranged from 25 to 38 for the various mirrors, and on the passenger side, the number of rated comments ranged from 6 to 17 for the various mirrors. Note that for the driver side there were 28 subjects, whereas for the passenger side there were 20. Because of this difference in sample size, it would be expected that fewer total comments would be available for the passenger side than for the driver side.

The driver side analysis resulted in significance for the mirror independent variable, $F(6,220) = 3.39$, $p = 0.0032$. The results are plotted in Figure 106, showing that the flat elongated mirror (F-E) received the highest experimenter ratings of the subject comments. This mirror was significantly higher in ratings than the C14, A20, and C20. Note also that the three latter mirrors had mean ratings somewhat below neutral, that is, values below 5.0. The results suggest that the flat mirrors received somewhat higher ratings than the other mirrors, although the F mirror was not significantly different from any of the curved mirrors. Several subjects praised the F-E mirror, which probably helped to create the significant main effect.

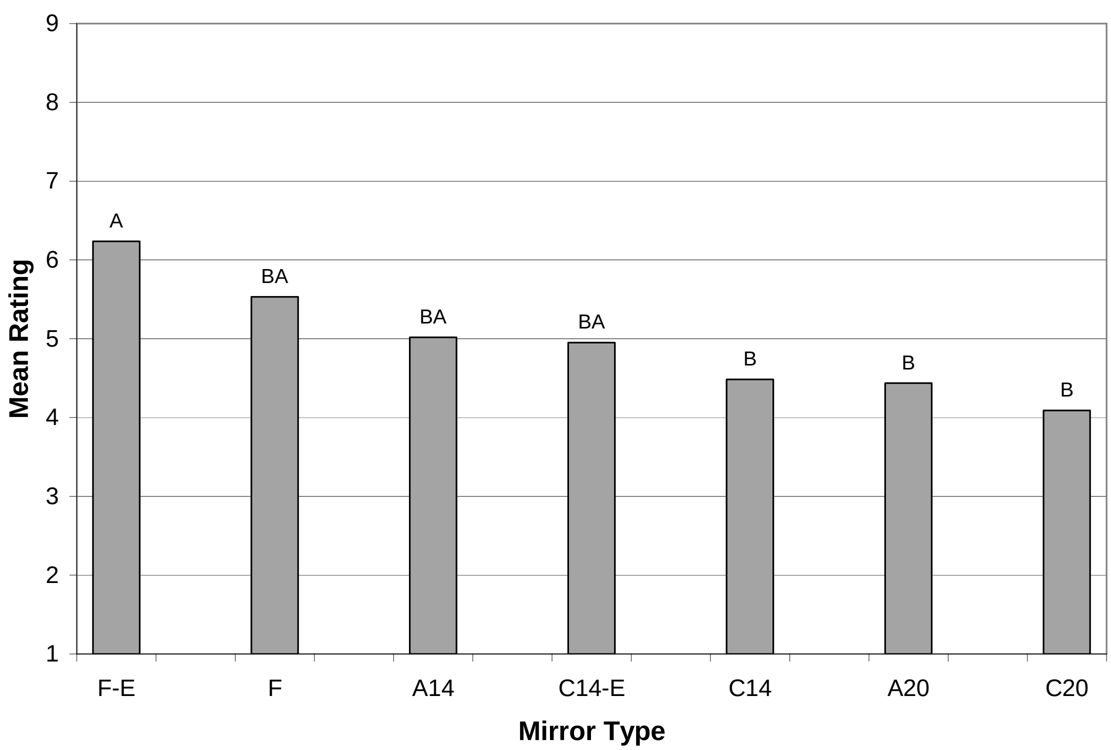


**Figure 106. Mean experimenter ratings of the degree to which comments made by the subjects were favorable/unfavorable, as a function of mirror, driver side.**

**Note that higher values indicate more favorable ratings, with 5 being the neutral value.**

On the passenger side, the analysis did not result in significance for mirror, with $F(4,64) = 1.6$, $p = 0.184$. There were no flat mirrors used on the passenger side. It is worth mentioning that on the passenger side, the C14-E, C10, and A20 mirrors received mean ratings below neutral; that is, below 5.0.

### Discussion of the On-Road Experiment Results

The results of the on-road experiment provide a general understanding of how drivers reacted to, and used, the various mirrors in situations they would be expected to encounter. As indicated earlier, the experiment was set up to answer the main remaining research questions using a near-operational, realistic, and safe environment. Test conditions were chosen to exercise the mirrors in scenarios deemed important.

### General Findings with Regard to Performance

The various graphs in this chapter show that while there are some domains of significance for performance as a function of mirror in some cases, actual differences in means are quite small. As examples, Figures 60 and 61, which show significant differences for the passing and merging tasks, had maximum performance differences of only about 7.7 ft (2.35 m). In the case of the last-comfortable-gap experiment, there was no domain of significance for the main effect of mirror. This occurred even though the experiment had a relatively high level of statistical power. Because differences are so small, it must be concluded that there are no practically significant differences in the various mirrors used on the driver side and there are none on the passenger side.

Why would such a result occur? The performance differences that were tested in this experiment, having to do with passing, merging, and pulling in front of oncoming vehicles suggest that drivers are, by and large, not relying on the outside mirrors for distance judgments. It seems they recognize that the various outside mirrors may be deceptive when it comes to distance and speed estimation, or at the very least they are using other methods to judge distance and speed.

The results of the experiment show that there are performance differences between the older and younger age groups. For example, Figure 63 shows in regard to passing and merging that older drivers cut in closer on passing and merging maneuvers. Note that in this figure the higher values for the decelerating merges correspond to shorter distances to the lead confederate vehicle. In regard to the last-comfortable-gap experiment, Figures 83 and 84 show that older drivers pressed the button at much larger distances. These differences show that older drivers feel they need more distance to pull out in front of an oncoming vehicle. Note that all these effects are largely outside-mirror-independent, that is, they occurred for all the various mirrors.

This experiment has, in general, shown that while performance differences as a function of mirror are sometimes significant, such differences are relatively small. This result is in agreement with the earlier work of Mortimer (1971) and Mortimer and Jorgeson (1974), who showed that when drivers were allowed to use their inside rear-view mirrors in combination with the outside mirror, performance differences were either nonexistent or small. Mortimer and Jorgeson did not include aspherics or elongated mirrors in their studies. Thus, the results of the current experiment go beyond that work. It is important to note that both the current study and the earlier work of Mortimer and Jorgesen underscore the importance of the *flat interior* rear-view mirror. This mirror *must* be available for use by the driver, because the driver relies heavily on it.

### General Findings in Regard to Eyeglance Behavior

Eyeglance behavior, which is indicative of how drivers gather information, is not greatly affected by outside rear-view mirror type. Figures 65 through 82 show that there were differences in the patterns used by older subjects as compared to younger subjects. For example, older subjects often spent more time looking at the forward view than younger subjects during the passing and merging events, whereas younger subjects used that time to look into the outside rear-view mirror. However, any differences associated with mirror type are small.

For the last-comfortable-gap experiment, once again, differences as a function of outside mirror are relatively small (Figures 86 to 91). However, older subjects, and to an extent younger subjects, used the flat outside mirrors on the driver side more than the other mirrors. When this occurred, the visual resource was taken from the interior mirror. In other words, subjects would time-share a bit more between the interior (flat) mirror and the outside mirror when the outside mirror was flat. Apparently, they trusted the flat mirrors on the outside when they were available. There is also some evidence that older subjects did not trust the C20 mirror on the driver side, because they spent less time looking into that mirror than for other mirrors and more time using the interior mirror than for the other mirrors.

The results of the current experiment show surprising consistency of eyeglance behavior as a function of mirror type, the exception being for the flat mirrors on the driver side, which were used a bit more. Note specifically that there were no passenger-side flat mirrors. As a result, the eyeglance patterns for the passenger side are highly consistent.

### General Findings in Regard to Opinion Data

All results in regard to opinion data should be prefaced with the reminder that the subjects examined the mirrors ahead of time and they were also read descriptions for each mirror. They then performed the various tasks with each specific mirror and then performed ratings for that mirror. Figure 45 shows the mirrors as provided to the subjects in the driver-side experiment, and Figure 47 shows the mirrors as provided to the subjects in the passenger-side experiment. Appendix D contains both the driver-side descriptions and the passenger-side descriptions read to the subjects. The descriptions could possibly have influenced the subjects, but it was decided that such a potential problem was less serious than use of subjects who might be totally ignorant of the variations in the mirrors. In particular, since the curvature of the mirrors could only be detected under careful examination, subjects could easily assume all the mirrors were flat and not substantially different from one another, except for size. In such a case results might not reflect the use of the mirror as it was intended.

Subject ratings results are found in Figures 92 through 105. On the driver side, (Figures 92 through 102) it became clear that drivers found coordination with the interior mirror as well as speed and distance estimation to be much better with the two flat mirrors. They rated the two aspherics and the C14 as moderately acceptable, that is, with average values around 5. Similarly, they rated the distortion and uneasiness as lower (higher rating) for the two flat mirrors and they rated the comfort level as higher. The C14, A20, and A14 fared relatively poorly, with moderate distortion, uneasiness, and comfort level.

There were additional differences as a function of age and gender. Figure 96 shows that for field-of-view, older subjects liked the flat and C14 mirrors better while younger subjects liked the A14, A20, and C14-E mirrors better. This difference could be a result of greater receptiveness to new mirrors. As another example, Figure 102 shows that older females rated the distortion worse (lower rating) than the other three age/gender groups.

On the passenger side, differences were somewhat smaller because flat mirrors were not used. Neither the coordination nor speed and distance estimation ratings exhibited significant mirror effects. In regard to Field-of-viewfield-of-view, only an age group effect was significant, and it showed that younger subjects rated higher (Figure 100). For Distortion, there was a mirror effect, with the C14 showing significantly less distortion than the A20. This mirror effect could be a result of familiarity with the C14, which is in common use on automobiles. In addition, older females rated distortion as significantly worse than the other age/gender groups. This type of result was seen earlier for the driver side.

The uneasiness ratings and the comfort level ratings were worse for the A20 than for the C14 (Figures 104 and 105). In addition, for comfort level, the C10 rating was worse than the C14. Here again, familiarity may have played a role.

These results, taken together indicate that on the passenger side, drivers found the alternatives to the C14 less acceptable. There seems to be a general reticence to accept the alternatives, including the aspherics.

When the experimenters analyzed the "free-form" comments, they found a similar pattern on the driver side (Figure 106). The F-E mirror received better ratings than the C14, A20, and C20. The two flat mirrors had the highest mean ratings, but the flat (non-elongated) mirror did not differ significantly from the other mirrors. On the passenger side, there was no significant difference among the mirror types.

### Answers to the Major Research Questions

1. In regard to the question, "Which mirrors, if any, create reductions in gap (clearance) during passing and merging maneuvers…?" it is clear that none of the alternative mirrors creates a substantial or hazardous reduction in gap. However, it must also be said the flat mirrors produce the largest gaps by a small amount.

2. In regard to the question, "Which mirrors, if any, create reductions in last comfortable gap for vehicles approaching from the rear in adjacent lanes?" the results show once again that differences are small with a range of only about 6 ft (1.83 m) and that, therefore, the alternative mirrors are not hazardous. Flat mirrors (on the driver side) again fared slightly better, but the differences are small.

3. In regard to the question, "Are there changes in driver visual scan patterns associated with candidate outside rear-view mirrors, and if so, what are the implications?" the results show only very small changes in scan patterns. Based on the patterns obtained, it is clear that *drivers rely heavily on their interior rear-view mirrors and the forward view to pass, merge, and determine acceptable gap.* They do use their outside mirror on the appropriate side, but not as the primary source. Nevertheless, when the outside mirror is flat, particularly the flat elongated mirror, they will use that mirror a bit more and the interior mirror slightly less. It is believed this is a result of trusting flat mirrors.

4. In regard to the questions, "What is the degree of initial acceptance (based on six different rating dimensions and a fill-in question) of the aspheric mirrors relative to current U.S. mirrors? Which mirrors, if any, from the driver's standpoint are preferred?" the results of the opinion data suggest that drivers prefer the mirrors currently found on light vehicles meeting current U.S. standards. When flat mirrors were present (driver-side experiment), these mirrors were by and large preferred. On the passenger side, the C14 was generally preferred, a mirror that is widely used on today's automobiles. Subjects rated the distortion, uneasiness, and discomfort as worse for the alternatives. These results suggest that initial acceptance of the alternatives was not high. Younger subjects tended to produce slightly higher ratings for the alternatives compared with older subjects who tended to produce lower ratings. Overall, however, the main effects of mirror demonstrate less acceptance of the alternative mirrors. Free-form comments (on the driver side) echo these findings.

5. In regard to the question, "Does age affect the performance, eyeglance behavior, or ratings as a function of mirror type?" the answer is a definite yes. Age appears to affect many aspects of the data, and gender also enters to a degree. In regard to passing and merging, there were cases where age caused smaller gaps at cut-in (Figure 63; note that the 1DM and 2DM correspond to smaller gaps to the lead confederate vehicle, as explained earlier). For the last-comfortable-gap experiment, the older age group had larger gaps that were on average twice as large as younger subjects, and this result was consistent on each side of the vehicle (Figures 83 and 84).

For eyeglance data, older subjects tended to use the forward view and interior mirror more than younger subjects, whereas younger subjects used the outside mirror a bit more. And in regard to opinion data, age interacted with mirror type and gender quite often. In particular, older females tended to provide lower ratings than did the other three age/gender groupings. Also, older subjects were more tolerant of mirrors with which they were familiar, whereas younger subjects were more tolerant of newer alternatives.

## Conclusions

This experiment has produced several findings that can be used to draw conclusions regarding alternative outside mirrors, with particular emphasis on aspherics. These conclusions are as follows:

- Outside rear-view mirrors do not play a major role in passing, merging, and determining last comfortable gap. It appears that drivers use their interior rear-view mirror as the primary source of reliable information, when rear-views are needed. However, when the outside mirror is flat (on the driver side), they may supplement the interior mirror with the outside flat mirror for reliable information.
- Outside rear-view mirrors at most cause only minor variations in cut-in and gap acceptance. Flat mirrors produce slightly more clearance than do other mirrors.
- Glance patterns support the above conclusions, but younger drivers do use their outside mirrors a bit more than older drivers.
- Opinion data suggest that drivers are somewhat reticent to accept the newer mirrors. They find the distortion, uneasiness, and discomfort to be somewhat more troublesome. This result differs substantively from the earlier results of Flannagan and Flannagan (1998) who found good acceptance of aspherics among Ford employees, even initially. In addition, Flannagan and Flannagan found higher levels of acceptance after extended use. The Ford employees could be considered to be much more knowledgeable than average drivers.
- There are other age and gender effects, which suggest that older drivers in general and older female drivers in particular are less likely to accept (or "like") the newer mirrors.
- It is believed that the experiment met the goals for providing the needed information in regard to aspherics and other types of alternative outside rear-view mirrors. However, as stated earlier, this experiment did not study the longitudinal (long term) effects of using the various alternative mirrors.

# PART V. PROJECT FINDINGS

# CHAPTER 20. PROJECT CONCLUSIONS AND RECOMMENDATIONS

## Information Gathering

The information gathering task described in Part I of this report shows very clearly that outside rear-view mirrors have been a subject of study for decades. A huge variety of mirrors has been tested and developed, but of course, as in many other areas of technology, few have survived to present vehicle applications. Even fewer have become standard on new vehicles.

Outside rear-view mirrors represent a compromise among many competing factors. Field-of-view, mirror size, reflected image size, glare, driver use, and driver acceptance are among the factors that must be considered. The United States has settled on a specific set of requirements for light vehicles and the European Union has settled on a somewhat different set. Initial indications from the information gathering task suggest that allowance for aspheric mirrors may be promising.

The general conclusions of the literature review are as follows:

- U. S. light-vehicle regulations do not specifically prohibit the use of aspheric mirrors. However, mirrors must in any case meet the regulations requiring a flat mirror on the driver side and a flat or convex mirror on the passenger side (if a passenger-side mirror is used). If a convex mirror is used on the passenger side, a precautionary legend must be included on the mirror reading, "objects in mirror are closer than they appear."
- Clearly, if an aspheric mirror is used on the driver side in the United States, it would have to have an infinite *vertical* radius of curvature, unless the regulations are modified to permit convex mirrors. On the passenger side, the outer aspheric portion must be in addition to a convex inner mirror that meets the U.S. regulations.
- E.U. regulations permit the use of aspheric mirrors on either side of a light vehicle. There are specific limits on curvature, but these do not impinge on currently accepted European mirror designs anyway (current E.U. aspheric mirrors are well within the specific limits on curvature). The regulations use a specific mathematical horizontal profile for aspherics, which is taken from Pilhall's (1981) formulation. This formulation is provided in the regulations without a clear explanation. For example, no coordinate system is defined. The current report has developed the details of the formulation.
- There is preliminary database information suggesting that vehicles equipped with aspherics are involved in fewer crashes than those equipped with flat mirrors. However, there is no reliable difference between vehicles equipped with convex mirrors and those equipped with aspherics. In other words, the difference in crashes is between vehicles with flat mirrors and vehicles with either convex or aspheric mirrors. (The databases examined were for European countries.)
- A flat mirror on the driver side of the vehicle appears to create a blind spot that is large enough to hide a vehicle. This blind spot is a result of lack of coverage occurring between head-turned direct view peripheral vision and the mirror view, which is relatively narrow.
- Aspheric and convex mirrors minify the image of an object when viewed in the mirror. In addition, *aspheric* mirrors create some image distortion which further narrows the horizontal dimensions of the corresponding image. Available information (in the litera-

ture) does not indicate whether this distortion creates a problem for drivers. However, aspheric mirrors appear to be accepted in the European Union, suggesting that the distortion is not a serious problem or is at least acceptable. In addition, a study done in the United States and limited to an auto manufacturer's employees indicated that they generally preferred aspherics to their regular mirrors. However, auto manufacturer's employees are not necessarily representative of the driving public. (The on-road experiments performed as part of current project suggest that aspherics would be less well accepted than current mirrors and that distortion *is* a problem.)

- The literature suggests that a careful look should be taken at aspheric mirror use by older drivers. Specifically, it is often found that older individuals are somewhat more susceptible to both discomfort glare and disability glare. (This matter was also investigated in the current project.)
- More generally, both aspheric mirrors and convex mirrors increase the field-of-view over that of flat mirrors. This advantage is offset by the loss of unit magnification of the image that is associated with flat mirrors. Therefore, assuming that unit magnification is a desirable feature, there is a tradeoff in going to aspheric or convex mirrors (loss of unit magnification vs. gain of a wider field-of-view).

### Derivations and Analyses

The analyses performed in Part II of this report indicate that many of the questions regarding aspheric, convex, and flat mirrors can be answered by straightforward analyses. Specifically, questions regarding image size, reflectivity, surface material reflectance, and mirror surface equations can be answered precisely using straightforward geometrical, optical, and mathematical considerations. Particular attention must be paid to getting the image minification factor associated with convex mirrors correct. To do so, derivations must be based on the angle subtended at the observer's eye. Otherwise, incorrect conclusions may be drawn.

Another important element of the analyses is obtaining a direct relationship between mirror radius of curvature and reflectivity. This relationship makes it possible to measure the characteristics of a mirror and then to determine both the mirror reflectivity as well as the surface material reflectance. The analyses show very clearly that as mirror radius of curvature decreases (that is, as curvature itself increases), image minification increases and mirror reflectivity decreases. This analytical background places the understanding of flat, convex, and aspheric mirrors on a solid footing and sets the stage for experimentation.

Specific conclusions from the analyses that were performed are as follows:

- An accurate assessment of image minification using a convex mirror requires a two step analysis. The first step is to calculate the virtual image distance and corresponding magnification (which is far less than unity), and the second step is to calculate the angle of the image subtended at the eye. This angle is compared to that occurring for a flat mirror in the same location. Image minification is itself an important specification of a convex mirror and in addition it can be easily related to mirror reflectivity.
- It is possible to relate image minification directly to mirror radius of curvature. The other parameters needed are the eye-to-mirror distance and the mirror-to-object distance (Equation 12, Chapter 7).

- It is also possible to calculate apparent distance to an object based on minification. (However, later experiments show that drivers do *not* estimate distance using minification alone, as will be summarized in the static experimentation summary that follows.)
- Image minification will be greater for a given mirror mounted on the passenger side of the vehicle than for the same mirror mounted on the driver side of the vehicle (Figure 6, Chapter 7). This is a result of the greater eye to mirror distance on the passenger side.
- Mirror reflectivity can be calculated by deriving the ratio of reflected illuminances (Equation 18, Chapter 8), and can be shown to be directly related to the square of the minification factor (Equation 19, Chapter 8).
- Radius of curvature of a mirror can be measured using a precision instrument (Figure 7, Chapter 9) and an appropriate derivation (Figure 8 and Equation 21, Chapter 9).
- Surface material reflectance can be measured directly for a flat mirror (Figure 9, Chapter 9), but must be derived from measurements for a convex mirror. This, however, is a straightforward procedure (Equation 25, Chapter 9).
- For typical convex mirrors used on the driver side of the vehicle, "looming" is not a serious problem until objects are within 10 ft (3.05m) of the mirror (Figure 10, Chapter 10). Consequently, at typical pass and merge decision distances (which are much greater than 10 ft), looming is not a problem.
- Similarly, although slightly larger on the passenger side, looming is not a problem at typical pass and merge decision distances (Figure 11, Chapter 10).
- The equations for the horizontal profiles of aspheric mirrors that are used in the European Union involve a constant radius inner portion and an additional cubic in the outer (aspheric) portion (Equation 29 and Figure 12, Chapter 11). It is possible to take a few geometric measurements and then completely specify the equations.
- Reflectivity from the aspheric portion of an aspheric mirror can be calculated (Equation 34, Chapter 11), provided that the point of reflection is specified. This reflectivity is always smaller than for the convex portion.

**Static Experimentation**

The six experiments described in Part III provide several results that are in agreement with the analytical studies and serve to verify those studies. However, new information is also obtained that goes beyond the analyses and could not have been predicted. In most cases this information has to do with driver responses to the mirrors.

Specific conclusions are as follows:

- Typical sets of mirrors obtained for a vehicle marketed in both the United States and the European Union were found to be relatively precise in that the nominal radii of curvature were close to the actual radii of curvature (Table 2, Chapter 12). Similarly, the nominally flat mirrors were in fact nearly flat.
- The mirrors had consistent surface material reflectances (Table 3, Chapter 12). These reflectances were calculated from equations derived in Part II, based on measured parameters.
- Objective in situ tests indicate that there is a sharp cutoff of light reflected into the driver's eyes by flat mirrors, and that these mirrors also create the highest reflectivity values by a wide margin. Cutoffs are at approximately 12 deg on the driver side and 7.5 deg on the passenger side (Figure 17, Chapter 13).

- The tests also indicate that the reflectivity decreases as the mirror radius of curvature decreases. Furthermore, the cutoff angles increase. For example, a 2,000 mm convex mirror has cutoffs of approximately 21 deg on the driver side and 16.5 deg on the passenger side. Aspheric mirrors, on the other hand, have a gradual cutoff (actually a roll-off). Consequently, while they have the same initial reflectivities as their corresponding convex mirrors, the reflectivities taper sooner and go out to larger angles (Figure 17, Chapter 13). These results indicate that aspheric mirrors have larger fields-of-view and will also pick glare from larger angles but with much lower reflectivities.
- The reflectivity results (see for example, Figure 18, Chapter 14) are useful in determining the relative fields of view of the various mirrors, both on the driver side and on the passenger side.
- The distance estimation experiment showed, surprisingly, that drivers generally underestimate the distance to objects seen in the driver-side rear-view mirror. Underestimation is "safe" estimation, because actual clearances are then greater than the drivers perceive them to be.
- Drivers do not appear to judge distance on the basis of image size. Image size for convex and aspheric mirrors is much smaller than for a flat mirror. A typical image size for a convex mirror would be half that of a flat mirror. This would correspond to an approximate doubling of the estimated distance and would result in a severe distance over-estimation, that is, a potentially dangerous situation (Equations 14 and 15, Chapter 7). Clearly, drivers have learned to compensate for the image minification that occurs with convex mirrors.
- Flat mirrors produce the greatest and most consistent underestimation (Figure 32, Chapter 16). The greater the mirror curvature (that is, the smaller the radius of curvature), the smaller is the amount of *underestimation*. In fact, for a nominal distance near 100 ft (30.5 m) and a radius of curvature of 1,400 mm there was a slight over-estimation of distance. The results are generally consistent with earlier work, showing that the amount of underestimation of distance decreases as mirror radius of curvature increases. The net effect of replacing flat mirrors with convex mirrors is likely to be that some clearances associated with merging and passing would be slightly smaller. There would also then be a greater likelihood of a collision owing to misjudgment of distance, but this must be traded against the likely increased probability of detection of nearby vehicles.
- The subjective experiment on headlight glare showed results consistent with previous analyses. Flat mirrors did indeed produce the highest ratings of reflected glare. At close distances, headlights move out of the field-of-view of the mirrors owing to their narrow field-of-view (Figure 38, Chapter 17).
- The outside mirrors generally produce glare ratings that are higher than those for an interior mirror that is adjusted to the manual nighttime setting. This indicates that typical outside mirrors are capable of producing substantially more discomfort glare, unless they are purposely darkened. However, darkening may affect daytime detection.
- Aspheric and convex mirrors having a 1,400 mm radius of curvature produce lower glare ratings than other outside mirrors tested, as compared with flat mirrors or mirrors with less curvature, as would be predicted by the reflectivity equations derived earlier. The glare ratings for 1,400 mm radius of curvature mirrors average about one rating

value higher in glare than the inside rear-view mirror in the nighttime setting (Figure 38, Chapter 17).

- Older drivers gave *lower* glare ratings than younger drivers at distances beyond 30 ft (9.1 m) (Figure 35, Chapter 17). While this result may appear not to agree with the literature, there was one previous study on headlight glare that did show this same type of reverse effect. In both cases, subjects looked directly into the glare source in making their ratings. It is believed that under these conditions, older subjects give lower ratings of glare. Examination of the data by subject shows no outlier effects (Figures 42 and 43, Chapter 17), suggesting that the current results are very likely to be repeatable and are therefore considered to be reliable.

### On-Road (Dynamic) Experimentation

The on-road experiment results were presented in the previous chapter. However, at the risk of being repetitive, they are briefly restated here. Note that all of these findings are associated with having the interior rear-view mirror available.

- On the basis of the results it appears that outside rear-view mirrors do not play a major role in passing, merging, and determining last comfortable gap. Drivers rely on their interior rear-view mirror as the primary source of reliable information, when rear-views are needed. However, when the outside mirror is flat (on the driver side), they may supplement the interior mirror with the outside flat mirror for reliable information.
- Outside rear-view mirrors at most have only a small influence on cut-in distance and gap acceptance. Flat mirrors produce slightly more clearance than do other mirrors.
- Glance patterns support the above conclusions, but younger drivers do use their outside mirrors a bit more than older drivers. Older drivers on the other hand look toward the forward view a bit more.
- Opinion data suggest that drivers are somewhat reticent to accept the newer mirrors. They find the distortion, uneasiness, and discomfort to be somewhat more troublesome. This result differs substantively from the earlier results of Flannagan and Flannagan (1998) who found good acceptance of aspherics among Ford employees, even initially. In addition, those employees also used the mirrors over a relatively long period of time. Flannagan and Flannagan found not only the high levels of initial acceptance, but also even better levels after extended use. The Ford employees could be considered to be much more knowledgeable than average drivers. Perhaps that is the reason for the difference in initial results. There are other age and gender effects, which suggest that older drivers in general and older female drivers in particular are less likely to accept (or "like") the newer mirrors.
- The elongated flat mirror on the driver side received relatively high ratings, but in general all performance differences as a function of mirror type were small.

### General Conclusions

This project has reviewed the available information on outside rear-view aspheric mirrors and their relationships to convex and flat mirrors. In addition, optical and mathematical analyses have been carried out for the various types of mirrors. And finally, both objective and subjective static experimentation as well as dynamic experimentation has been performed to verify and add to the understanding of the various mirrors and how they are used.

The advantages of an aspheric mirror are as follows:

- It provides a substantially larger field-of-view than a corresponding flat mirror.
- The on-road experiments demonstrated no major performance *disadvantages* in ordinary passing, merging, and gap acceptance.
- It provides a larger field-of-view than a corresponding convex mirror (having the same radius of curvature as the spherical part of the aspheric mirror).
- It appears to induce fewer crashes than a corresponding flat mirror. (A convex mirror also appears to induce fewer crashes than a corresponding flat mirror.)
- Driver acceptance of an aspheric mirror appears to be satisfactory, based on the literature. However, the on-road dynamic experimentation performed during the current project indicates otherwise. Subjects indicated reticence by their ratings of distortion, uneasiness, and discomfort.
- Peak glare is substantially less for a typical aspheric mirror as compared with a flat mirror. The glare rolls off more rapidly than for a convex mirror (but does go out to larger angles).
- Older drivers generally rate the glare from outside mirrors lower than younger drivers for headlight distances at or beyond 30 ft (9.1m). Glare reflected from an aspheric does not create an additional burden of discomfort for older drivers (as compared with younger drivers) at least for the case where drivers are looking directly into the mirror.
- Drivers are generally able to compensate for the non-unit magnification of an aspheric (in its convex region) or convex mirror in terms of distance estimation. Generally (but not always), drivers underestimate distance to objects slightly.

These advantages are offset by disadvantages associated with an aspheric mirror:

- It produces image distortion in its outer (aspheric) portion. This distortion "squeezes" the horizontal dimension relative to the vertical dimension. The on-road tests indicated lower ratings for these mirrors as a result of the distortion.
- Since an aspheric provides a wider field-of-view, it then will pick up additional glare sources. However, these additional sources will be greatly attenuated.
- The amount of underestimation of distance that will occur with an aspheric (or with a convex mirror) will be less than for a flat mirror. Underestimation is a safety factor in that the true distance to an object is greater than the perceived distance. It is possible therefore that an aspheric (or convex) mirror may cause slightly smaller clearances during passing and merging, as well as an occasional collision. However, preliminary accident analyses performed by other researchers suggest that these types of collisions are more than offset by increased angular detection capability.
- All drivers, but particularly older drivers (and even more particularly female older drivers) appear reticent to accept and use aspheric mirrors, as evidenced by their ratings of distortion, uneasiness, and discomfort.
- Unit magnification, which is used by drivers to judge distance, is only available with flat mirrors. Convex and aspheric mirrors do not have unit magnification. Consequently, unit magnification will be lost if the current driver-side mirror is replaced with an aspheric (or convex) mirror.

**Recommendations**

The reader can interpret the results of the various studies that have been performed. Consequently, while recommendations will be made, it is possible that readers may disagree with them based on the sum of the evidence presented. There is no "correct" or unique answer regarding what recommendations should be made, since the results demonstrate tradeoffs that can be resolved in various ways. Nevertheless, the experiences gained in performing the tasks documented in the current report seem to point in specific future directions which are described in this section.

In making the recommendations, it should be recognized that the driver-side outside mirror problem is somewhat different from the passenger-side outside mirror problem. While both were studied in the current report, the two sides should be given separate consideration for reasons that have already been stated.

Recommendation 1. Based on all evidence, it is clear that aspheric mirrors are not a panacea. They have advantages and disadvantages. There is risk associated with permitting them to be used in place of current mirrors on light vehicles, particularly on the driver side. The main risk appears to be lack of acceptance or lack of adaptation. Another risk is loss of the unit magnification attribute on the driver side of the vehicle. The type of aspheric used in the European Union cannot be used on the driver side in the United States without modification of CFR §571.111. Therefore, prior to any change in the standard, it is believed that a fleet study should be performed over a substantial period of time, perhaps three to six months. The purpose of this study would be to examine the longitudinal (that is, the time-related) effects of using aspherics. As with the on- road experiment reported in the current report, performance, eyeglance, and opinion data should be gathered. If the results are sufficiently promising, it might then be prudent to permit the use of aspherics on the driver side. It should be noted that current standards allow use of aspherics on the passenger side as long as the convex portion (in and of itself) of the aspheric mirror meets current standards. However, there is currently no mention of aspherics in the standard, so they are basically unregulated (except that the convex portion must meet all elements of the current standard).

By performing a longitudinal study, it should be possible to determine if drivers adapt to the new mirrors. In addition, by examining incidents and any crashes, it might be possible to make an assessment of the potential reduction in sideswipe crashes resulting from the likely advantage of elimination of blind spots.

Recommendation 2. The current research report indicates that there has been no experimental attempt to study the supposedly increased detection capability of aspherics in a practical setting. Only optical fields of view were studied (see Chapters 14 and 15). This remaining element could be studied using an approach developed for heavy vehicles (Jenness, Llaneras, & Huey, 2005) in which electro-transmissive window coverings were used to assess how quickly and how accurately drivers of heavy vehicles could detect targets (other vehicles and objects) in their mirrors. All work was done statically, that is, with the vehicle under test standing still. While this approach has limitations, it might be helpful in determining if drivers can actually use the aspheric portion of aspheric mirrors. It would not be necessary to use electro-transmissive panels. Instead, the outside mirror under test could simply be blocked from view to limit the visual sample time, as called for in the report by Jenness et al. (2005). Such a test should shed light on the potential accuracy of detection, accuracy of identification, and response time. Of course, comparison tests are always preferred, so it would prudent to include competing mirrors in the test.

It should be understood that testing of this type might be indicative, but it would not be conclusive. Since tests would be performed statically, even positive results for aspherics would have to be checked by some type of on-road study.

Recommendation 3. It is believed that there are potential alternatives for outside mirror design, other than the aspheric. For example, all heavy vehicles have a flat mirror by regulation and a convex mirror by recommended practice on each side of the vehicle (Spaulding, Wierwille, Gupta, & Hanowski, 2005). The two mirrors are used in combination to obtain an adequate field-of-view and simultaneous indication of "true" distance where needed. It would seem that some derivative of this design could be used for light vehicles. Another alternative is to take advantage of video technology to enhance the field-of-view and eliminate blind spots. It should be possible to develop video displays at the A-pillars or another location close to the current actual mirrors for purposes of wide angle viewing and elimination of blind spots. Alternative concepts are suggested in the following section.

The above three recommendations all involve additional studies. This work would be directed toward *demonstrating* the main potential advantage of aspherics or other types of newer designs, namely greater detection capability. Once again, it should be remembered that there are actually two decisions to be made: permitting aspherics on the driver side, and permitting aspherics on the passenger side. Note that current regulations do not prohibit use of aspherics on the passenger side, provided that the aspheric meets the requirements by means of its inner convex portion.

### Alternative Concepts

Recommendation 3 involves the development of alternatives for outside rear-view mirror design. In this section, a few alternative concepts are suggested. In all cases, the primary objective is to provide the driver with a blind-spot free or blind-spot reduced visual field. Emphasis here is on the driver side, but some of the concepts would also apply to the passenger side. Six concepts are presented and explained briefly. Those alternatives which are limited to the driver side may require duplicate cosmetic housings on the passenger side so that vehicles appear balanced.

Alternative 1. This alternative uses the space below the present-day mirror on the driver side of the vehicle. In this space, a convex mirror is added which provides a wide-angle view (Figure 107). The convex mirror would be affixed to the current flat mirror above, so that a single mirror adjustment mechanism could be used. The convex mirror could be set so that it provides a view of the normal blind spot that exists for the flat mirror by itself. Note that the space below the current mirror is easily seen by the driver. In addition, this space does not in and of itself block any view that is needed by the driver. Also, if the convex mirror is affixed to the upper flat mirror, it can be optimized to provide a view that is complements the flat mirror. Consequently, the required curvature can be kept relatively mild (radius of curvature can be kept large) while still providing full coverage. Figure 108 shows how the convex mirror complements the flat mirror.

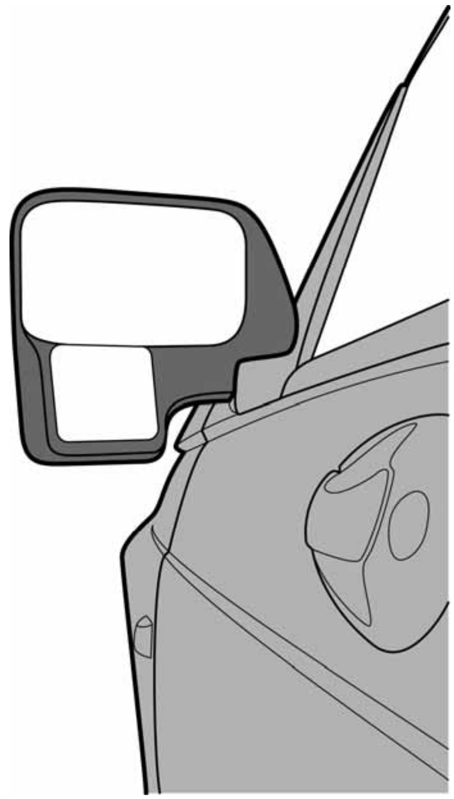

**Figure 107. Concept of a convex mirror affixed below the current flat mirror, driver side.**

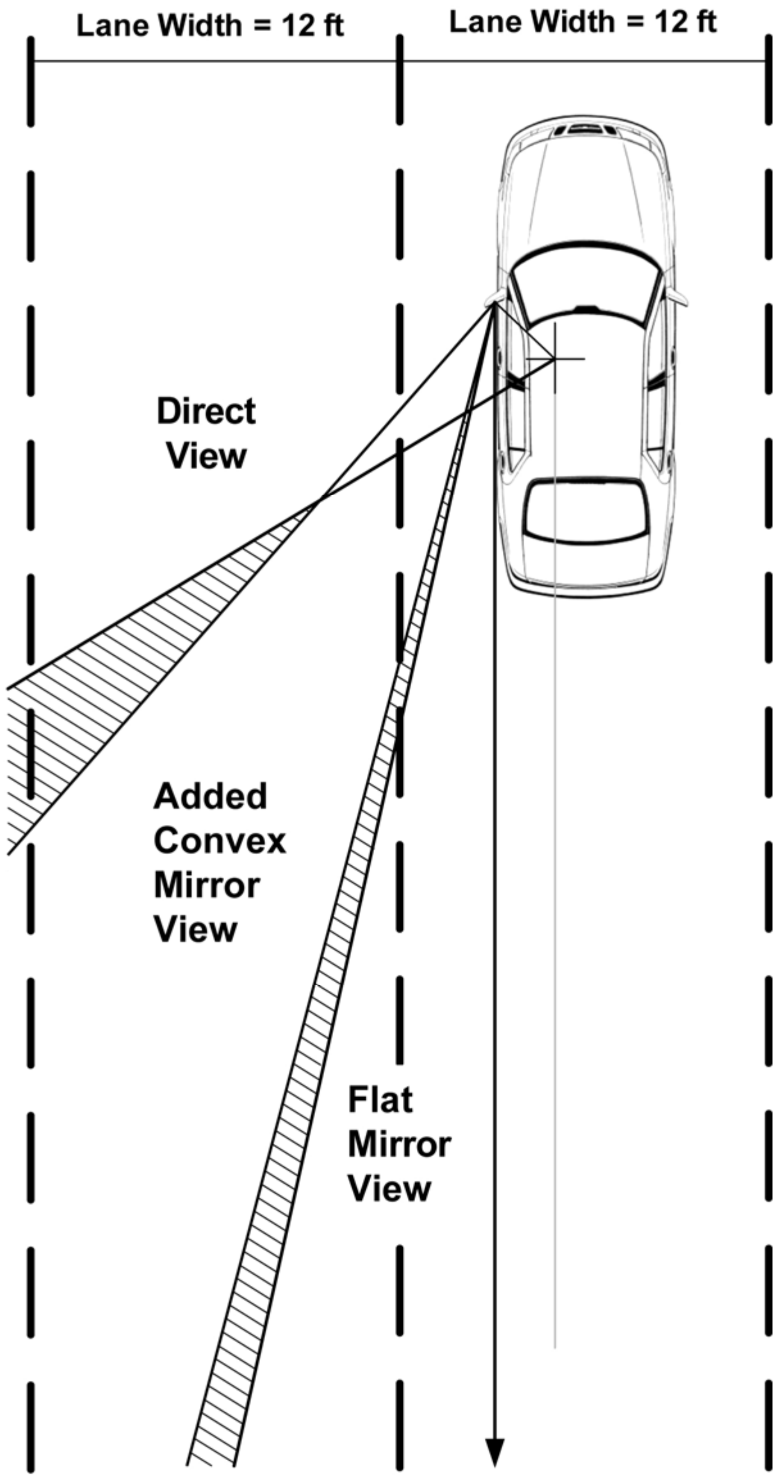


**Figure 108. Additional coverage afforded by a convex mirror below the current flat mirror, driver side.**

Alternative 2. This alternative is similar to Alternative 1. However, in this case, the lower mirror is flat. It is offset to cover the center of the blind spot. The concept in this case is to provide a second "true size" image of the middle of the blind spot. Doing so would make it less likely that any relatively large object could be completely hidden in the usual blind spot (Figure 109). As with Alternative 1, the added mirror could probably be aimed by the same mechanism as the upper mirror, since the geometric relationship between mirrors should be nearly constant.

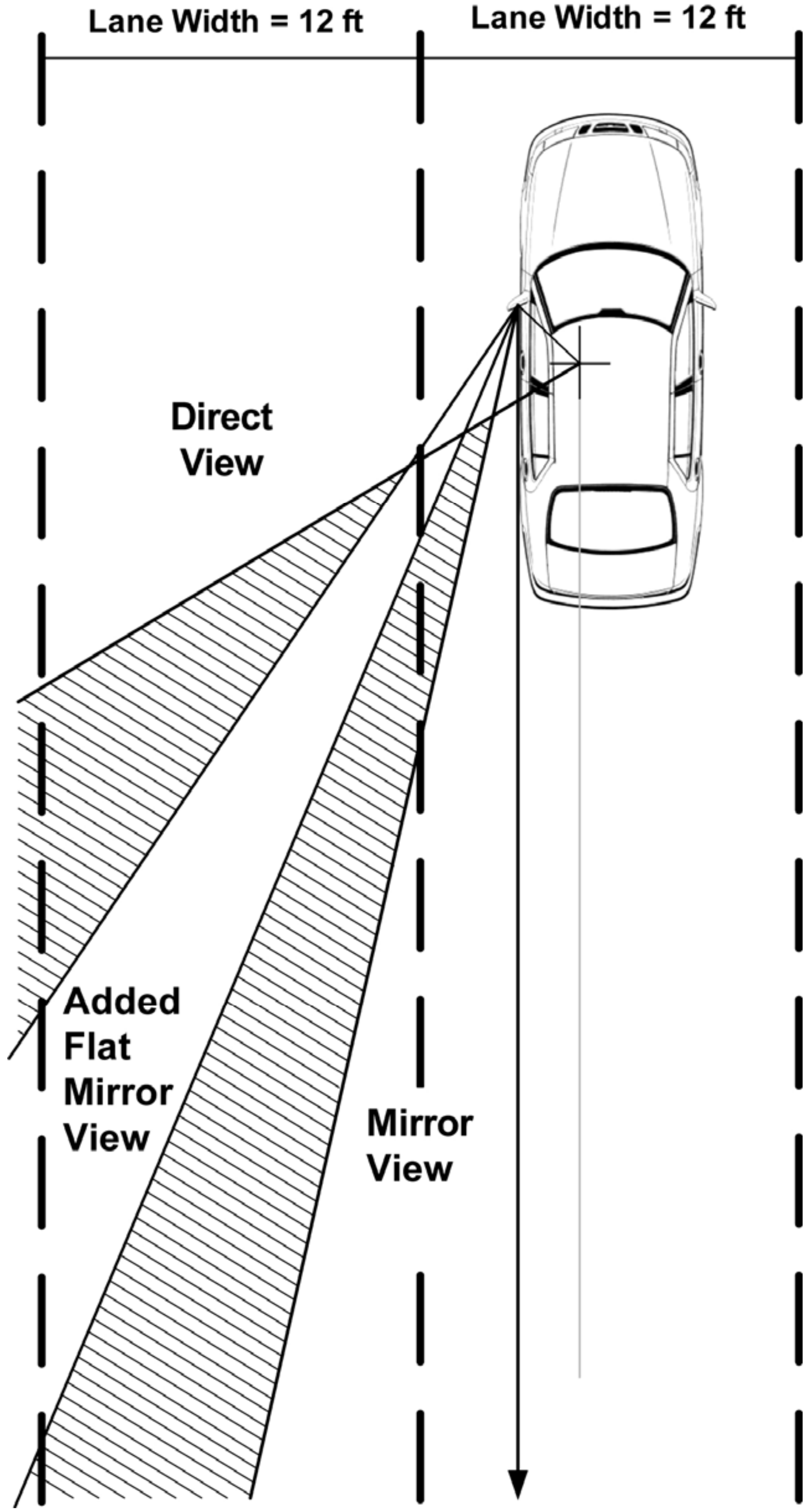


**Figure 109. Additional coverage afforded by an additional flat mirror below the current flat mirror, driver side.**

Alternative 3. This alternative takes advantage of video technology to provide the additional view to cover the blind spot (Figure 110). The field-of-view of the camera lens would determine the degree of coverage of the blind spot. The camera aim and field-of-view values could be set to match the views shown in Figure 111. The camera could be placed along the roofline of the light vehicle and aimed in the direction of the blind spot. Other camera locations are also possible. The monitor could be placed outside in a fixed position under the adjustable flat mirror. Note that use of video would likely preclude the need for aim adjustment, because the desired view would be largely independent of driver eye position, unlike the use of mirrors which require adjustment as a result of driver eye position. If an LCD (liquid crystal display) is used, heating may be necessary in cold weather. However, many late model light vehicles have heated mirrors, so it would be a relatively straightforward addition to heat the display when needed.

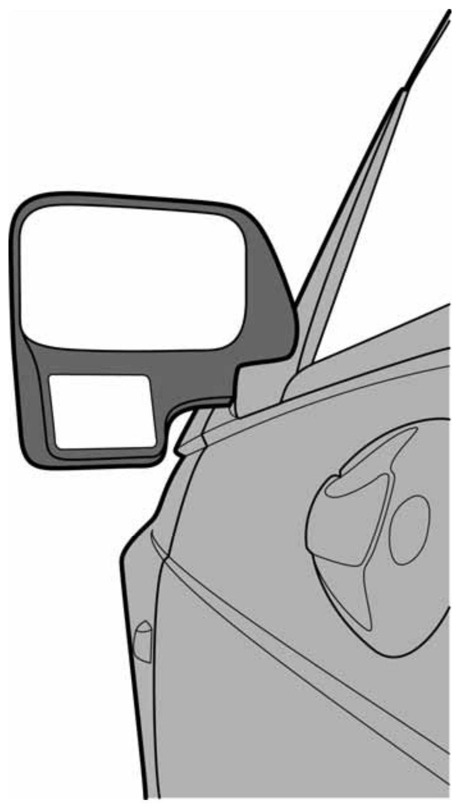

**Figure 110. Video monitor below the mirror, driver side.**

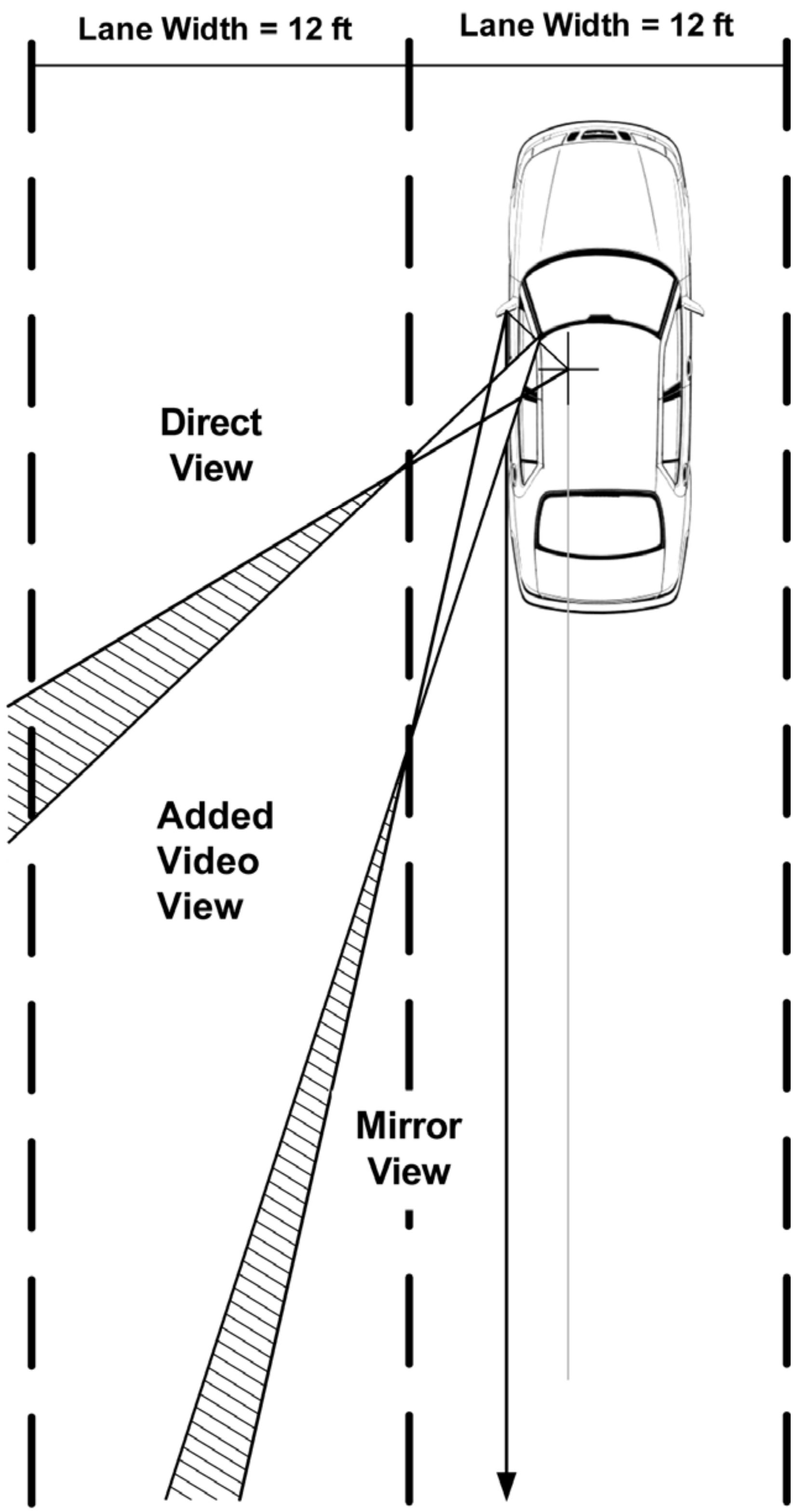


**Figure 111. Additional coverage afforded by a typical video camera mounted at the front corner of the vehicle roof, driver side.**

Alternative 4. This alternative is similar to Alternative 3, except that the display is placed at the A-pillar (Figure 112). This approach could be used on either the driver or passenger side. The advantage of this approach is that the displays are in the passenger compartment of the vehicle, which is less subject to adverse weather (except possibly heat buildup when the vehicle is parked).

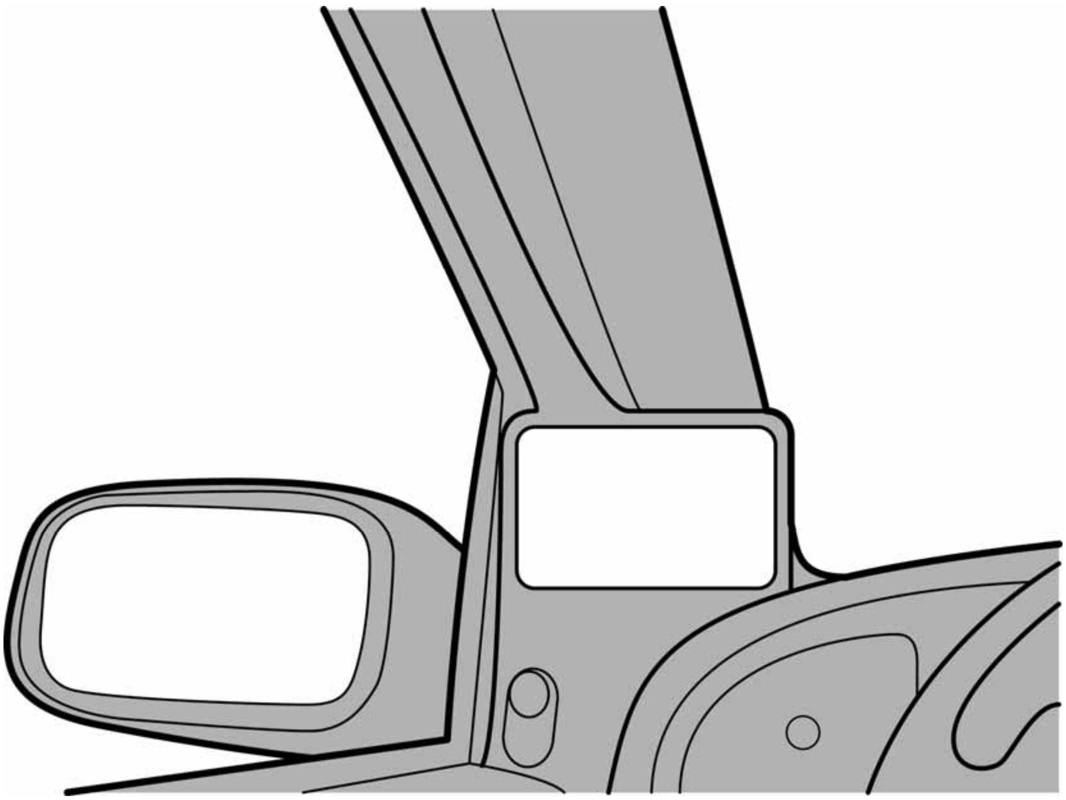

**Figure 112. Video monitor mounted at the A-pillar, driver side.**

Alternative 5. This alternative is already under development and test. It uses radar or laser technology to determine if the blind spot is clear. The driver receives a go/no-go indication when the directional signal is activated. Indicators can be placed at the A-pillar or mirror on the side of directional signal activation.

Alternative 6. This alternative is also already under development. It cycles the driver-side mirror aim point laterally when the driver activates the driver-side turn signal. This process provides a sweep of the blind spot on the driver side of the vehicle. If a blind spot exists on the passenger side, the same type of arrangement could be employed there.

The alternative arrangements suggested here do not have the problems of visual distortion created by an aspheric mirror. In addition, on the driver side, use of the flat mirror is preserved. However, these alternatives may have problems of their own. Consequently, development and human factors testing would need to be performed to uncover any shortcomings and to optimize the designs.

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# APPENDIX A: SUBJECT INSTRUCTIONS FOR THE DISTANCE ESTIMATION EXPERIMENT (CHAPTER 16)

The purpose of this experiment is to obtain estimates of how far away vehicles appear with three different types of rear-view mirrors. Your participation will involve estimating the distance to the vehicle appearing in your driver's side outside rear-view mirror. You will give three estimates, one for each of three different mirrors at three different corresponding object vehicle distances. This experiment is expected to take about 10 minutes.

Please estimate the apparent distance on the basis of the way the vehicle appears in the mirror. You should ignore the background behind the vehicle, but you can look forward at a reference vehicle which will be explained to you. Also, please don't try to figure out how the experiment is being run. We just want you to estimate the distance based on the image of the vehicle in the mirror. In other words, just tell it like it is.

The vehicle in the mirror may be located at a distance that is a round whole number, such as 95 feet, or it may be located at a distance that is a non-round whole number, such as 97 feet. In other words, it may be at any whole number distance. Consequently, your estimate may be any whole number, that is, a round number or a non-round number.

You will first look down into your vehicle, with hearing protection earmuffs on, until the object vehicle is in its position and the mirror you are to use has been attached. Once I give you the signal, you will look into the mirror, adjust it quickly, and then give me a distance estimate.

While estimating, you may compare the image in the mirror to the vehicle parked ahead. The vehicle ahead is different model of vehicle, but the vehicle is **exactly 100 feet** away.

Once you have adjusted the mirror, you have 10 seconds in which to give me an estimate. You can look forward at the reference vehicle during the 10 seconds if you want to. Your estimate should be in feet.

Do you have any questions?

## APPENDIX B. SUBJECT'S RATING FORM, DYNAMIC ON-ROAD EXPERIMENT

Subject Number: ___________________ Mirror Code: ____________

### Ratings for this outside rearview mirror

In performing the following ratings, bear in mind that the outside rearview mirror and the center interior mirror represent a combined system for assessing situations to the rear and side of your vehicle. The first two ratings address the combined system.

### <u>Coordination</u>

I am able to coordinate the use of this outside mirror with the center interior mirror.

| | | | | |
|---|---|---|---|---|
| Poor Coordination | Somewhat Inadequate Coordination | Moderate Coordination | Good Coordination | Excellent Coordination |

### <u>Speed/Distance Estimation</u>

I am able to estimate the speed and distance to another vehicle using this outside mirror in combination with the center interior mirror.

| | | | | |
|---|---|---|---|---|
| Poor Speed/Dist. Est. | Somewhat Inadequate Speed/Dist. Est. | Moderate Speed/Dist. Est. | Good Speed/Dist. Est. | Excellent Speed/Dist. Est. |

### <u>Field-of-View of the Outside Mirror (By Itself)</u>

When using this outside mirror by itself, I find the field-of-view (F.O.V.) of the outside mirror to be

| | | | | |
|---|---|---|---|---|
| Completely Inadequate F.O.V. | Somewhat Inadequate F.O.V. | Moderately Adequate F.O.V | Mostly Adequate F.O.V. | Totally Adequate F.O.V. |

**Distortion**

When looking into this outside mirror, I would rate the distortion of the image as

| Extreme Distortion | Heavy Distortion | Moderate Distortion | Mild Distortion | No Distortion |
|---|---|---|---|---|

**Uneasiness**

When looking into this outside mirror, I sense the following level of uneasiness

| Extreme Uneasiness | Substantial Uneasiness | Some Uneasi-ness | Slight Uneasiness | No Uneasiness |
|---|---|---|---|---|

**Comfort Level**

I would feel comfortable using this outside mirror on my vehicle

| Very Uncom-fortable | Somewhat Un-comfortable | Moderately Comfortable | Quite Comfortable | Completely Comfortable |
|---|---|---|---|---|

Any additional comments you would like to make regarding this mirror.

1. ______________________________
2. ______________________________
3. ______________________________

## APPENDIX C. INFORMED CONSENT FORM, DYNAMIC ON-ROAD EXPERIMENT

**Virginia Polytechnic Institute and State University**
**Informed Consent for Subjects**

**Title of Project**: Study of Driver Performance/Acceptance using Aspheric Mirrors in Light Vehicle Applications; Test Road Experiment Using Aspheric Outside Rear View Mirrors

**Experimenters:** Jeremy M. Spaulding, William A. Schaudt, Santosh K. Gupta, Walter W. Wierwille, Michael P. Greening, and Richard J. Hanowski

### I. The Purpose of this Research

Outside rear view mirrors on automobiles are being constantly improved. Countries in the European Union are beginning to use a new type of mirror called an "aspheric" mirror. This mirror has a conventional portion toward the inside and a more curved portion toward the outside, so that it has a larger field-of-view. Moreover, the overall size of a mirror may have an effect on the way distance is perceived. To determine the advantages and disadvantages of these mirrors, VTTI needs to perform tests with ordinary drivers. You are being asked to serve as a driver on the Smart Road while using these mirrors. For purposes of comparison, you will also drive with mirrors similar to your own car and with some other alternatives, to be explained to you. In all, you will use seven (five) different mirrors. If you decide to participate, you will provide ratings for each of the different mirrors. In addition you will participate in determining the last-comfortable-gap experiment which will be explained to you. Your total participation will take approximately 4 hours (3 hours).

### II. Procedures

We will first ask you to show us your driver's license. Thereafter, we may need to run a simple vision test. Assuming you pass the vision test, we will explain the procedures further. First, we will describe procedures to you here in the VTTI research building. Thereafter, we will take you to the research vehicle and you will drive onto the Smart Road where additional procedures will be explained before the first run.

Here in the building you will first decide if you want to participate. If so, you will sign your name at the end of this form, so indicating. You should only sign after you have read and understood this form and had your questions answered.

Next we will show you exact duplicates of each of the mirrors to be used during the experiment. Each mirror will be explained to you, and you will be able to examine each mirror. After that, you will receive a general explanation of each "run."

Runs are each composed of two complete loops (or circuits) of the Smart Road. The outbound portion of a loop will consist of several merge maneuvers with VTTI drivers driving two other vehicles, whereas, the inbound portion of the loop will consist of last-comfortable-gap assessment. During the inbound portion of the loop you will follow a lead vehicle at a distance of 125 feet. This distance will be demonstrated to you at the beginning of the inbound portion of the loop. The lead vehicle will travel at 30 miles per hour.

Upon entering the Smart Road, an experimenter will instruct you where to pull over and stop so that further instructions can be explained. Thereafter, the first loop will allow you to get a feeling for the experiment and what you will have to do (with no data being taken). After the first loop data will be taken on all other loops.

As indicated, the outbound part of a loop will involve your performing various merge maneuvers. During this time, an experimenter will instruct you to merge in front of, or in between, the two other vehicles at certain times. When you perform these maneuvers, you should look into your side mirror and into your interior mirror as you normally do. A total of three merge maneuvers will be performed during each outbound leg.

The inbound part of a loop will involve making judgments for last comfortable gap." An overtaking vehicle will approach from the rear and come alongside. It will then slow and move back. This process will be repeated several times. You will look into the side mirror and into your regular interior rear view mirror as you normally would. The overtaking vehicle will approach several times, and each time you will indicate the last comfortable gap by pressing a button just behind the right edge of the steering wheel. You will be able to activate the pushbutton without taking your hand off the wheel. You will be given an exact definition of last comfortable gap; but for now, all you need to know is that last comfortable gap is the last instant you would feel *comfortable* accelerating and changing lanes in front of an oncoming vehicle. You **will not** actually perform the maneuver for this portion of the experiment; instead, you will just press the button, as explained.

After you have completed the second loop of the Smart Road for each given mirror, you will temporarily stop the vehicle and provide ratings on a rating sheet for the given outside rear view mirror. The ratings sheet will be shown to you while you are still in the VTTI research building, and again, of course, each time you complete a run and stop to do the ratings.

There will be seven (five) runs altogether, that is, one for each of the mirrors. For each run, the procedures will be the same. Just prior to each run, the mirror type will be explained to you once again.

We have a break scheduled after you have completed four (three) runs. This will give you a chance to refresh and get a drink of water (we will return to the research building for this break). Once you have completed all of the runs, we will again return to the research building, where you will be paid, your remaining questions will be answered, and you will be dismissed.

### III. Risks and Discomforts

The risks you will face in this experiment are probably smaller than you would face in driving on a highway. Both of the VTTI drivers have been trained to avoid a crash, and no other vehicles will have access to the Smart Road. Consequently, we believe this is a minimum risk experiment.

One possible mild discomfort is associated with length of this experiment. It will take about 4 hours (3 hours) to complete. However, we have scheduled a break half way through the runs, so that you can refresh. Another possible mild discomfort may result from using mirrors to which you have not been previously exposed. We do not believe these discomforts are appreciable.

**IV. Benefits of this Project**

There are no direct benefits to you for participating in this research (other than normal subject payment). No promise or guarantee of benefits has been made to encourage you to participate. You may find the experiment interesting, and your participation may help in selecting better rear view mirrors for automobiles.

**V. Extent of Anonymity and Confidentiality**

The ratings that you provide in this experiment will be treated with anonymity. Your name will be kept separate from your ratings. Similarly, your name will be kept separate from your pushbutton responses and other data for the runs. Analysis of all data will be based on the pooled responses of those who complete participation. At this time, it is anticipated that 48 drivers will participate. Thus, it will be impossible in reporting the results of the experiment to identify any particular subject.

While you drive in this experiment, your eye position will be recorded by video. This is done by aiming a small video-camera at your face. After completion of your participation, the recordings will be used for research purposes only and will be analyzed to extract your eye positions. The recordings will be kept secure until they are no longer needed. They will then be erased.

**VI. Compensation**

You will receive payment in the amount of $20 per hour for your time and participation. This payment will be made directly to you at the end of your voluntary participation.

**VII. Freedom to Withdraw**

You should know that you are free to withdraw from the experiment at any time and for any reason without penalty. No one will try to make you continue. If you do not want to continue, you will be paid for the actual amount of time you participated. You are not required to answer any questions or to respond to any research situations, and you will not be penalized for not responding. The experimenter also has the right to end the experiment, if in his opinion it is best to do so.

**VIII. Approval of this Research**

Before data can be collected, the research must be approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Tech and by the Virginia Tech Transportation Institute. You should know that these approvals have been obtained.

**IX. Subject's Permission**

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I understand that I may withdraw at any time without penalty.

________________________________________ ____________________________

Subject's Signature Date

Should you have any questions about this research or its conduct, please contact:

| | |
|---|---|
| Richard Hanowski, Principal Investigator | (540) 231-1513 |
| Walter Wierwille, Research Scientist | (540) 231-1543 |
| Jeremy Spaulding, Research Associate | (540) 231-1579 |
| William Schaudt, Research Associate | (540) 231-1591 |
| Santosh Gupta, Research Associate | (540) 231-1049 |
| Michael Greening, Research Associate | (540) 231-1507 |
| David Moore, Chair, Institutional Review Board | (540) 231-4991 |

# APPENDIX D. MIRROR DESCRIPTIONS GIVEN TO SUBJECTS, DYNAMIC ON-ROAD EXPERIMENT

**<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, and the field-of-view is still a little narrow. 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.

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