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13. ABSTRACT (Maximum 200 words)

Due to the requirement for a planar rearview mirror on the driver side of light vehicles, and drivers' typical aiming of rearview mirrors, a large blind spot is adjacent to the car. This blind spot can conceal a vehicle, which may increase the risk of lane-change collisions. Non-planar rearview mirrors present the driver with a greater field of view; however, they also provide a minified image. Laboratory and stationary-driver testing have consistently shown that non-planar mirrors are associated with overestimations in distance and speed. However, there is less consistency in findings for on-road testing, as the magnitude and practical effect of overestimation varies. Likewise, lane-change crash rates in Europe do not appear to be affected by non-planar mirror use. The ability of drivers to detect and react to an object is aided by non-planar mirrors. This, and the interior planar rearview mirror, may offset overestimation and the effect of smaller accepted gaps. Additional research is needed to determine the effect of non-planar rearview mirrors on crash rates and driver acceptance, as well as the possibility of different configurations, of non-planar mirrors within the United States.

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EXECUTIVE SUMMARY

United States (U.S.) Federal Motor Vehicle Safety Standards (FMVSS) require the use of a planar (flat, or unit magnification) mirror on the driver side of a passenger automobile. Although planar mirrors provide an undistorted and non-minified virtual image to the driver that supports accurate judgments of vehicle distances and approach speeds, these mirrors do not have an increased field of view (FOV) relative to convex or aspheric mirrors. The European Union (E.U.) allows the use of both planar and non-planar (convex and aspheric) mirrors on the driver side of passenger vehicles. Aspheric mirrors are multiradius mirrors with a spherically convex inner portion and an aspheric (or decreasing radius of curvature) outer portion. While these non-planar mirrors provide an increased FOV for the driver, they also produce a minified, or reduced, image size. This minification effect is the primary source of concerns regarding driver judgments using non-planar mirrors. In order to address these issues, literature regarding the use of non-planar rearview mirrors was examined.

In general, a convex mirror of the same size and shape will present a smaller apparent image (a minified image) as compared to the image presented by the same size and shape planar mirror. Thus, there is interest in increasing FOV by the use of non-planar driver side rearview mirrors. However, many of the increases in FOV provided by a non-planar mirror may be lost by drivers' non-optimal adjustment of the rearview mirror. European data indicate no global statistically significant differences in lane-change crashes between vehicles with non-planar and planar mirrors.

There are fairly consistent laboratory and stationary-driver testing findings that suggest drivers overestimate distances (in terms of the driver estimating a greater *own vehicle to rearward approaching vehicle distance* than is actually present) when using non-planar mirrors. The amount of overestimation appears to be directly related to the convexity of the mirror. On-road testing (including test tracks and naturalistic observation data collection), where the driver is actively controlling a moving vehicle, has provided mixed results. These findings typically indicate that when drivers are allowed to sample from all mirrors on their vehicle they produce either smaller overestimations (reflected in reduced size of accepted gaps in lane changes) or have no measurable difference in performance as compared to planar mirrors. However, when overestimations are present, the differences between planar and non-planar mirrors are smaller than would be predicted based on laboratory and stationary-driver testing. Drivers are able to detect objects faster in non-planar mirrors. It also appears that drivers do not rely exclusively on the exterior rearview mirrors when making lane changes; instead, the interior rearview mirror appears to play a large role in driver mirror sampling prior to executing a lane change. Therefore, non-planar mirrors on the driver side of the light vehicle may not represent a safety disbenefit.

Subjective opinions regarding non-planar rearview mirrors are also unclear. Early testing indicated that drivers appreciated the large FOV provided by non-planar rearview mirrors. Additionally, some recent testing with a limited population has indicated that drivers quickly become comfortable with their everyday use. However, testing with a more general population indicated that drivers (especially females and the elderly) may have lower subjective opinions of the minified images (as compared to planar mirror images) produced by non-planar mirrors. Evidence supports the idea that drivers' subjective opinions will improve and judgment

performance will improve after initial exposure to non-planar mirrors, although judgment performance may not reach the levels obtained from using a non-planar mirror.

Advanced rearview mirror systems, such as systems including multiple mirror types in the same frame, may help to offset some of the performance issues with non-planar mirrors. Because of the discrepancies between laboratory and stationary-driver and on-road test results, as well as the variability present within on-road test results, further (real world, longitudinal) testing of both non-planar rearview mirrors and advanced mirror systems is needed in order to draw firm conclusions regarding their safety on the Nation's highways.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

cm	Centimeter
DOT	U.S. Department of Transportation
EC	European Community
ECE	(United Nations) Economic Commission for Europe
E.U.	European Union
FMVSS	Federal Motor Vehicle Safety Standard
FOV	Field of View
GVWR	Gross Vehicle Weight Rating
HID	High Intensity Discharge
kg	Kilogram
km	Kilometer
km/h	Kilometers per Hour
lb	Pound
m	Meter
mm	Millimeter
MPV	Multi-Purpose Vehicle (minivan)
NHTSA	National Highway Traffic Safety Administration
n.s.	Not Significant
p	Probability
PATH	(California) Partners for Advanced Transit and Highways
ROC	Radius of Curvature
s	Second
SAE	Society of Automotive Engineers
SD	Standard Deviation
SI	International System of Units (modern metric)
TRIS	Transportation Research Information Services
TTC	Time To Collision (Contact)
UFOV	Useful (Functional) Field of View
UN	United Nations
U.S.	United States

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CHAPTER 1. INTRODUCTION

BACKGROUND

Scope

Years of research have been conducted with the purpose of improving driver indirect vision. This is by no means a trivial task, as indirect vision provides critical information to drivers during merge, lane-change, turning, and backing maneuvers. Vehicle mirror systems (consisting of the interior and driver/passenger side rearview mirrors) have long been used to provide drivers with information about the areas surrounding their vehicles. Non-planar mirror systems (such as convex and aspheric mirrors) hold the potential to provide even more information than planar (flat, or unit magnification) mirrors provide, further reducing the blind spots around the vehicle. However, questions regarding the effect of non-planar mirrors on driver judgments have kept these types of mirrors from being adopted in the United States (U.S.).

Current U.S. regulations require a planar mirror on the driver side of a passenger automobile. This mirror provides an undistorted and non-minified virtual image to the driver, supporting accurate judgments of vehicle distances and approach speeds. The European Union (E.U.) allows for both planar and non-planar (convex and aspheric) mirrors on the driver side of passenger vehicles. While these non-planar mirrors provide an increased field of view (FOV) for the driver, they also provide a minified image to the driver with a reduced image size as compared to that of a planar mirror. This minification effect is the primary source of concerns regarding driver judgments using non-planar mirrors. This report summarizes an effort undertaken on behalf of the National Highway Traffic Safety Administration (NHTSA) to search and summarize the extant literature and research on the use of non-planar mirrors in light vehicles.

Overview and a Historical Context

Concurrent with the development of the automobile, and particularly early automobile racing, the importance of an awareness of vehicle surroundings was apparent. However, achieving this level of situational awareness was difficult or impossible for a driver actively controlling an automobile. Bockelmann (1991) claims that one of the earliest people to supplement driver situational awareness through indirect vision was Harroun, who placed a mirror on a racing car in 1911. This process relieved Harroun of the need for a passenger acting as a spotter, providing a racing advantage.

The development of improved indirect vision systems continued at a rapid pace. One such attempt at improved vehicle indirect vision is found in a patent awarded to Chester A. Weed in 1914 (U.S. Patent No. 1,114,559; Figure 1). Weed noted that an increasing number of drivers were mounting mirrors to the windshield and fenders of their cars. These mirrors described in Weed's 1914 patent employed both planar and non-planar (convex) mirrors, which the author stated would allow the driver to accurately determine "the exact location of a vehicle on the road in the rear" (para. 2). Interestingly, the patent filing also described the increasing number of drivers seeking to attach a reducing [convex] mirror in order to yield a wider FOV. Weed did not view this as a wise action without the addition of a planar mirror, as non-planar mirrors provide an image "known to every automobilist, it is deceptive and therefore dangerous, in that it is impossible to determine exactly how far back the vehicle in the rear may be, for in this mirror a vehicle may seem to be a long distance in the rear when as a matter of fact it is only directly in the rear of the car… (para. 4)."

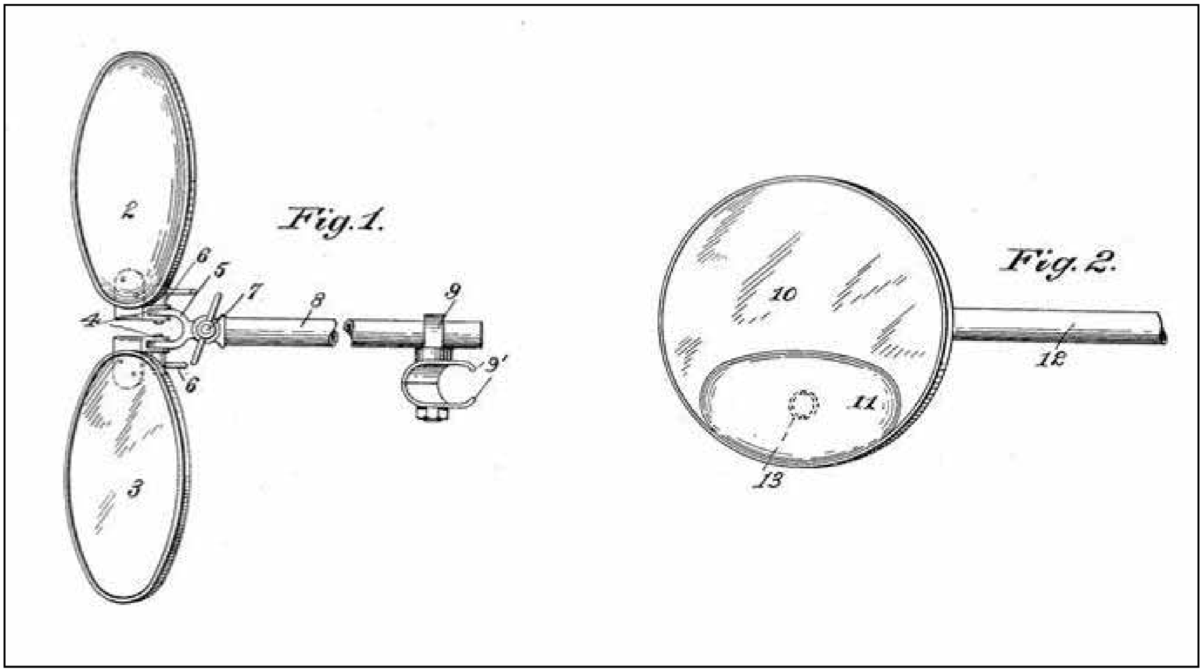

Figure 1. Illustrations from Weed's 1914 Patent Filing for an Automotive Mirror

The demands of driving, and especially our understanding of the FOV requirements needed to safely operate an automobile, have changed dramatically over time. In response to this, efforts to improve indirect vision systems for automobiles have been undertaken (Burger, 1974). Technologies such as non-planar rearview mirror systems attempt to deliver a wider FOV for drivers (Platzer, 1995). Non-planar mirrors are those with either a constant radius of curvature (ROC; such as a convex mirror) or a ROC that decreases across the horizontal width of the mirror (such as an aspheric mirror). Planar rearview mirrors, consisting of a flat surface (effectively, an infinite ROC), provide a more limited FOV while providing a non-minified image which appears to support driver estimations of distance and approach speeds. The increases in FOV provided by convex and aspheric mirrors are accompanied by minification in the image which may offset any benefits in blind-spot coverage. However, efforts to provide drivers' vision within their blind spots is of great importance, as most lane-change collisions occur without other explanatory factors such as weather or unusual road hazards (Eberhard, Luebkemann, Moffa, & Young, 1994) and may be considered to be failures of the driver to detect adjacent traffic.

Insufficient FOV is a likely causal factor in a number of vehicle collisions (Mortimer & VanderMey, 1971). Non-planar mirrors have the potential to increase the FOV provided to the driver, reduce blind spots around the vehicle, and have a palliative effect on the number of mirror-related collisions that occur. Potential problems and safety concerns with non-planar mirrors include a number of factors related to driver judgment. Due to the convexity of non-planar mirrors, both aspheric and convex mirrors present the driver with a minified image (images that are smaller in proportion than the real object). However, to gain an increased FOV, mirror convexity (and, thus, the minification produced by the mirror) must be increased. This leads to an image which drivers may have difficulty in perceiving and interpreting. Exterior rearview mirrors (mirrors mounted on the front fender or doors of the vehicle) augment the information provided to the driver through the interior rearview mirror (which is affixed to the dashboard or windshield of the vehicle).

The United States has established safety regulations for the use of exterior rearview mirrors on vehicles (§571.111; Office of the Federal Register, 2002) that require the use of an interior and driver side planar mirror. For passenger cars, this Federal Motor Vehicle Safety Standard (FMVSS 111) only requires a passenger side mirror if the interior review mirror cannot provide an FOV meeting FMVSS 111 specifications. For minivans (multi-purpose vehicles, or MPVs), light trucks, and buses (other than school buses) with a gross vehicle weight rating (GVWR) of 4,536 kg (10,000 lbs) or less, mirrors can conform to passenger car requirements or must have driver side and passenger side outside mirrors. Vehicles with a GVWR greater than 4,536 kg must have outside mirrors on both sides. Although the driver side rearview mirror must be a planar mirror, in 1982 the standard was amended to allow the use of a convex rearview mirror on the passenger side of the vehicle if FOV requirements are not met by the inside mirror. Due to minification, if a convex rearview mirror is used on the passenger side, it must be accompanied by an indelible marking on the mirror surface stating that “Objects in Mirror Are Closer Than They Appear," and the ROC of the mirror must be between 889 and 1651 mm. Additionally, FMVSS 111 requires that the ROC of a convex mirror cannot deviate by more than ±12.5 percent of the average ROC.

Furthermore, manufacturers are allowed to include additional types of mirrors (including both convex or aspheric) on the driver side location, provided the minimum requirements of FMVSS 111 are met. For instance, a driver side mirror may have an aspheric or convex section, provided there is a planar section present that meets FMVSS 111. Some auto manufacturers have begun to use this approach; Ford has introduced such a mirror (containing a planar mirror with an inset convex mirror in the upper outboard corner of the planar mirror; Figure 2).

Figure 2. Ford Blind Spot Mirror

In comparison to U.S. standards, light vehicles sold in the European Community (EC) must have driver and passenger side exterior rearview mirrors. These mirrors must meet a minimum requirement of providing an FOV consisting of a 4 m wide, flat, horizontal portion of the road that extends 20 m behind the driver's ocular points (eye location). These mirrors are allowed to include planar and non-planar surfaces. Further, both spherically convex and aspheric mirrors are allowed. If a spherically convex mirror is used, a minimum ROC of 1200 mm is specified, while the minimum ROC for an aspheric mirror section is 140 mm. Further, if an aspheric mirror is used, the transition between the convex and aspheric sections must be marked with a line (2003/97/EC; European Parliament & Council, 2003).

Since non-planar mirrors are allowed on E.U. vehicles, examining collision involvement based on exterior rearview mirror configuration may provide a better understanding of the potential benefits or costs from allowing their use on U.S. roads. Schumann, Sivak, and Flannagan (1996) examined British lane-change crash data recorded between 1989 and 1992, identifying the types of mirrors on vehicles and comparing the relative risk of a driver side crash (where mirrors can be planar or convex) to a crash on the passenger side (where mirrors are all convex). Their analysis indicated no global decrease in the number of driver side lane-change collisions for vehicles equipped with convex driver side rearview mirrors. However, there was a significant age effect present. Younger age groups (drivers 17-24 years old) had a significantly lower driver side lane-change collision involvement rate (approximately 35 percent) when driving a vehicle with convex driver side rearview mirrors. Older drivers (ages 65 and older) had a 46 percent decrease; however, this did not reach significance (Figure 3). Based on these results, the authors concluded that the use of convex driver-side mirrors appear to benefit high risk age groups (younger and older drivers) more than the rest of the adult population.

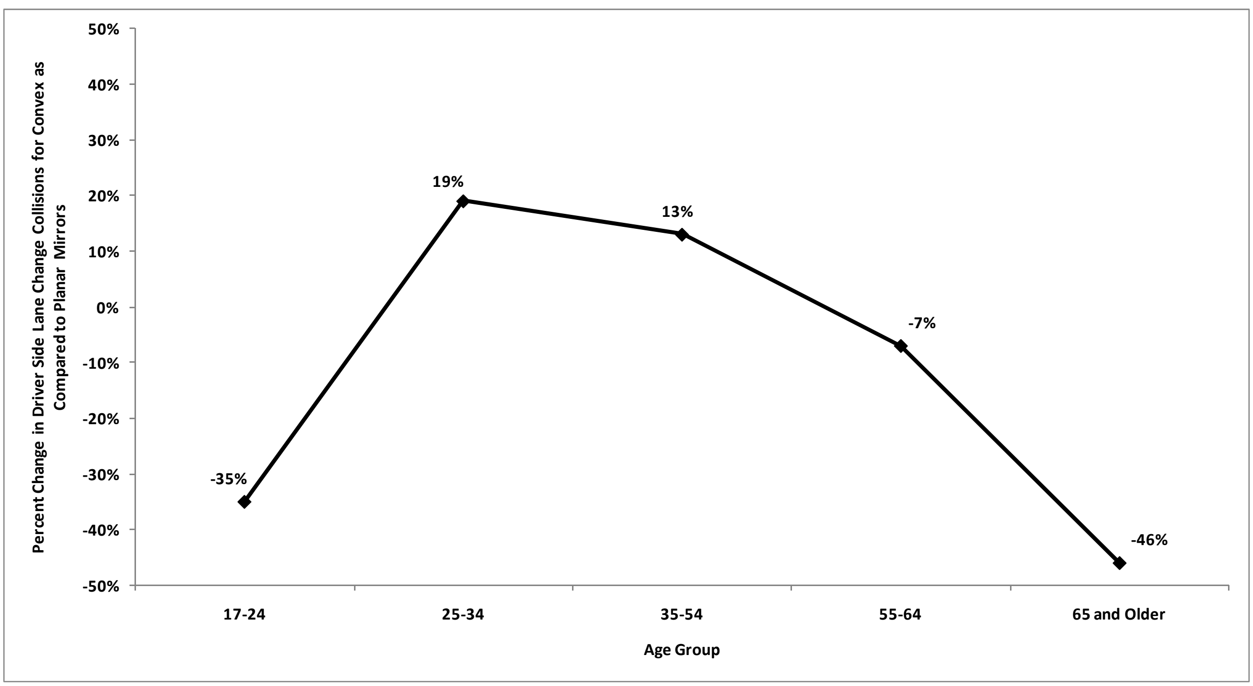

Figure 3. Percent Change in Driver Side Lane-Change Collisions for Convex as Compared to Planar Mirrors (adapted from Schumann et al., 1996)

Luoma, Flannagan, and Sivak (2000) examined data from 1,062 lane-change crashes occurring between 1987 and 1998 obtained from Finnish insurance companies. These data contained vehicle details allowing the authors to determine the type of driver side rearview mirror installed (planar, convex, aspheric) alongside the standard convex passenger-side-mounted rearview mirror. Crashes occurring on the passenger side of the vehicle were calculated and used as a base level of exposure. Forty-nine percent of the crashes occurred in a lane change to the driver side, while 51 percent occurred during a lane change to the passenger side of the vehicle. Results indicate that the use of non-planar mirrors (including both aspheric and convex mirrors) was associated with a 22.9 percent decrease in lane-change collisions. Although there was a 25.5 percent decrease in lane-change collisions for aspheric versus planar mirrors, this difference was not statistically significant. Likewise, convex mirrors demonstrated a non-statistically significant 20.6 percent decrease in lane-change collisions (Figure 4).

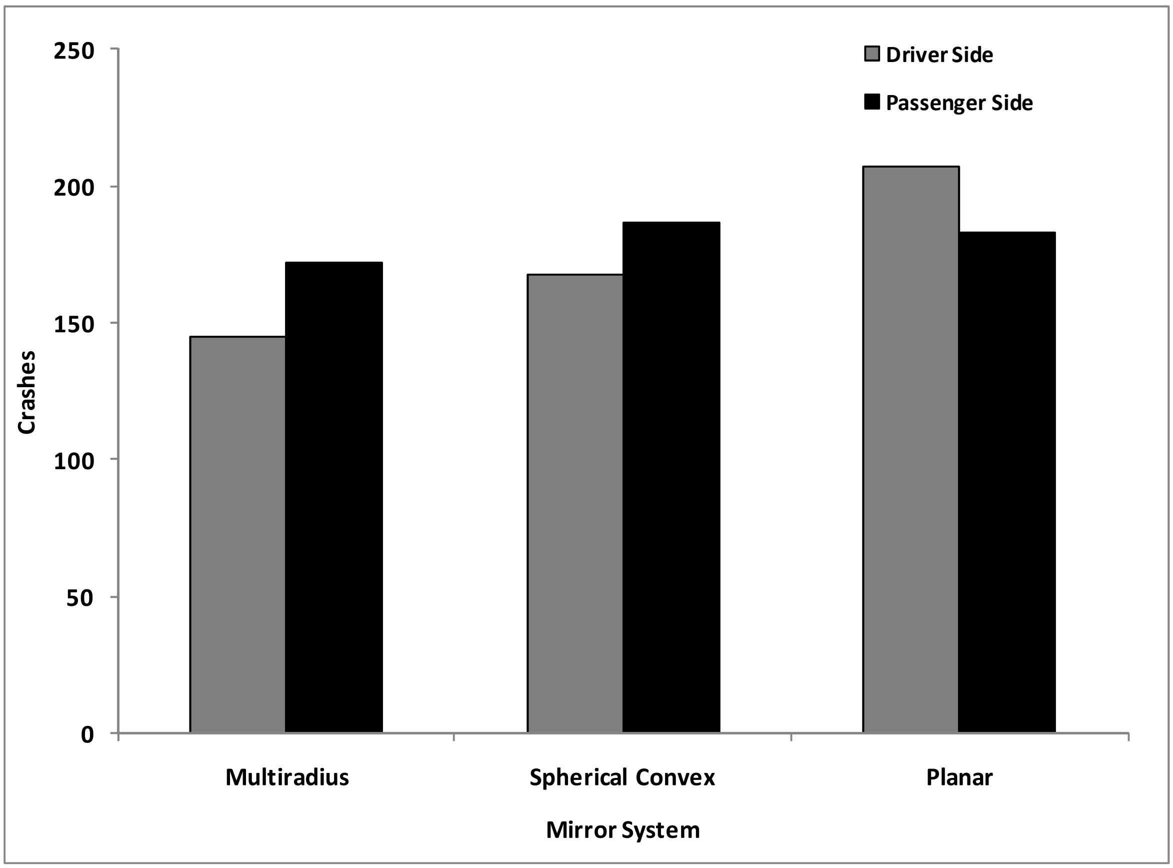

Figure 4. Crashes per Side by Mirror Type (adapted from Luoma et al., 2000)

Luoma, Flannagan, and Sivak (2000) also examined crash involvement and mirror type data for possible age group differences. Non-planar mirrors were associated with decreases in crash involvement for the youngest (18 to 24 years) and the oldest (55 and older) age groups (Figure 5). The results of this study are similar to findings of earlier work (Luoma, Sivak, & Flannagan, 1994; Luoma, Sivak, & Flannagan, 1995), indicating a 22 percent decrease in lane-change collisions with non-planar mirror use, and no difference between aspheric and convex mirrors for the number of lane-change collisions. Overall, these findings help illustrate potential benefits from non-planar mirror use (especially among certain high risk age groups); however, limitations in the data with respect to pre-crash data, as well as the lack of consistent exposure data, preclude drawing firm conclusions.

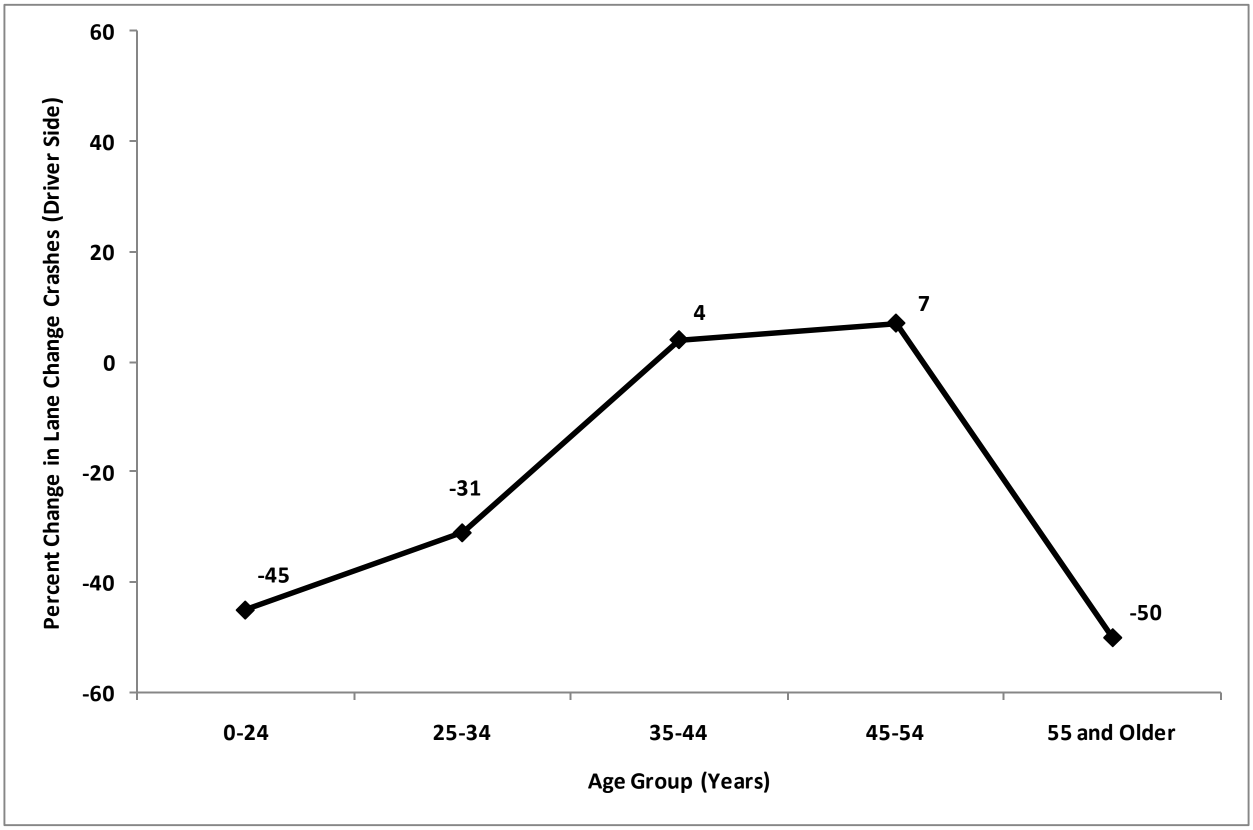

Figure 5. Percent Change in Driver Side Lane-Change Crashes by Age Group (adapted from Luoma et al., 2000)

These data indicate that, for some driver populations, vehicles with non-planar (not necessarily limited to aspheric mirrors) driver side rearview mirrors may be involved in fewer lane-change collisions as compared to vehicles equipped with planar driver side rearview mirrors. However, it is important to note that the studies producing these findings were carried out in the European Union. There are important differences in roadway conditions, vehicle types, traffic densities, and driver characteristics that preclude a direct comparison to U.S. highways. Yet the finding is informative that drivers may be able to take advantage of the additional FOV provided by non-planar rearview mirrors.

Information Gathering Process

Although the subject of years of research, non-planar mirror research findings are widely dispersed. This limits the availability of information for researchers and decision makers. In order to gather a variety of information on non-planar mirror research, multiple sources were queried. The initial results of these efforts were provided to experts (identified with the assistance of the Task Order Manager) in the field of automotive indirect vision. These experts provided valuable feedback as to the completeness of the literature search efforts.

The initial search effort consisted of queries in prominent databases and archives for several terms related to vehicle indirect vision. Key search terms used included mirror, rearview mirror, planar, non-planar, aspheric, convex, and side view. Combinations of these search terms were also used. These searches were queried in the following databases: Transportation Research Information Services (TRIS), NHTSA report and literature archives, EBSCOHost, SAE International, UC Berkeley Transportation Library (PATH), and the authors' institutional library and databases.

The initial search efforts were filtered for relevance to the scope of the current study (i.e., human performance issues related to aspects of non-planar rearview mirrors). Following this, all references within these sources were examined for relevance. Attempts were made to retrieve all relevant references from within the initial search results. This reference list (consisting of 88 works) was sent to the identified reviewers (Drs. Michael Flannagan, Juha Luoma, Ronald Mourant, and Walter Wierwille) for feedback as to the search results' completeness. The final reference list containing feedback from these reviewers and additional search efforts consisted of 130 items (including peer-reviewed papers, reports, technical standards, regulations, and patents) covering a period of over 40 years. When presented in this synthesis, all results and mirror descriptions are provided in SI (International System of Units, or modern metric) units to facilitate comparison between findings.

Summary

Although both planar and non-planar rearview mirrors have a long history, questions regarding human performance with non-planar rearview mirrors have persisted. Non-planar mirrors, such as convex and aspheric mirrors, provide an increased FOV at the expense of a minified image. Current U.S. regulations require the use of a planar-driver side rearview mirror, although non-planar mirrors are permitted on the passenger side and on the driver side when accompanied by a planar mirror. In contrast, the European Union allows for planar, convex, and aspheric rearview mirrors on the driver and passenger side positions. Comparisons between vehicles with and without non-planar driver side rearview mirrors have not indicated significant benefits, or have only indicated benefits to certain populations, from the application of convex and aspheric mirrors in terms of reduced lane-change collisions. However, the data for these studies were not obtained in the United States, precluding a direct comparison.

This work summarizes the research into non-planar mirror systems occurring during the past 40 years. In order to achieve this, an in-depth literature search was performed in a number of databases. The references of these works were also examined for sources, and the resulting final reference list was sent to outside reviewers to ensure complete coverage of the field. Results are summarized in terms of mirror configuration and human performance issues. In an effort to extend the usefulness of this literature synthesis all units of measure were standardized to SI units, a bibliography containing abstracts for relevant research in non-planar mirrors and indirect vision has been included in an appendix (Appendix A)

CHAPTER 2. DEFINITIONS AND TYPES OF MIRRORS

DEFINITIONS OF KEY CONCEPTS

Prior to discussing the various forms of mirrors and their applications, it is necessary to define terms related to their specification and application.

Driver's Field of View

The SAE J985 (1967; reaffirmed 2002) and J1050 (2003) definition of the driver's FOV for each eye is a horizontal plane totaling 150 degrees (90 degrees laterally from the sagittal plane, extending 60 degrees beyond the sagittal plane). The two overlapping monocular FOVs combine to form a binocular FOV of 120 degrees, centered on the sagittal plane and extending 60 degrees to either side. Vertically, this field is approximately 50 to 55 degrees above, and 60 to 70 degrees below, the forward line of sight.

While definitions for FOV are provided for situations with the head fixed, rotations of both the eyes and head that functionally increase the FOV are possible. SAE J985 defines optimal eye rotations as 15 degrees horizontally or vertically, with up to 30 degrees horizontally and 45 degrees upward/65 degrees downward as acceptable. The standard defines easy head movements as being up to 45 degrees horizontally/40 degrees vertically, with maximum head movements of 60 degrees horizontally and 50 degrees vertically.

Blind Spots

Definitions of a vehicle's blind spots are traditionally based on an assumption of a 180 degree direct FOV for the driver (Flannagan, Sivak, & Traube, 1999). This number is likely an overestimate of a driver's FOV, as has been noted by many researchers (Burg, 1968; Platzer, 1995) and technical standards (SAE, 1967). However, taking the hypothetical 180 degree direct FOV combined with the typical mirror location and aim used by drivers (Flannagan, Sivak, & Traube, 1999), the area between 13 and 45 degrees laterally from the vehicle's side is not covered by mirror vision (Figure 6). This blind-spot area is large enough to conceal an adjacent vehicle, creating the possibility of a collision during a lane-change maneuver.

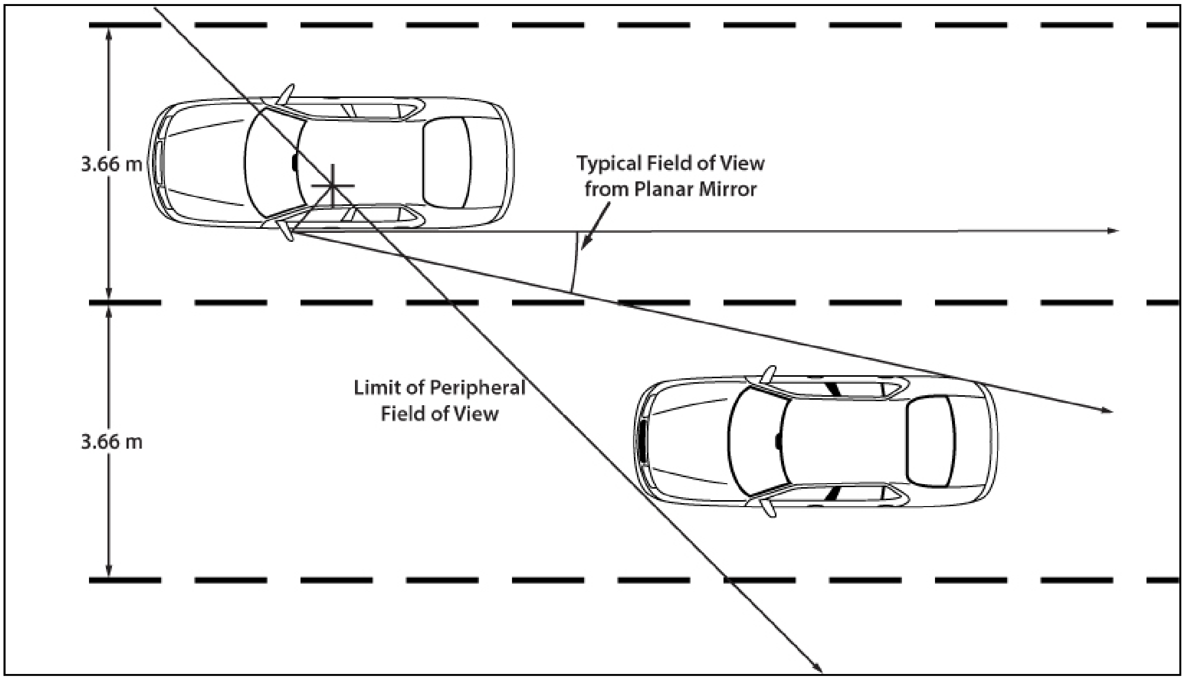

Figure 6. Vehicle Blind Spot Location Concealing an Adjacent Vehicle (adapted from Wierwille et al., 2008)

Eyellipse

The eyellipse, defined in SAE J941 (2008; Figure 7), represents a range of anthropometric elliptical range of locations for the driver's eyes in the vehicle. For a 95 percent eyellipse, 95 percent of driver cyclopean eyes will lie to one side of a plane tangent to the ellipse.

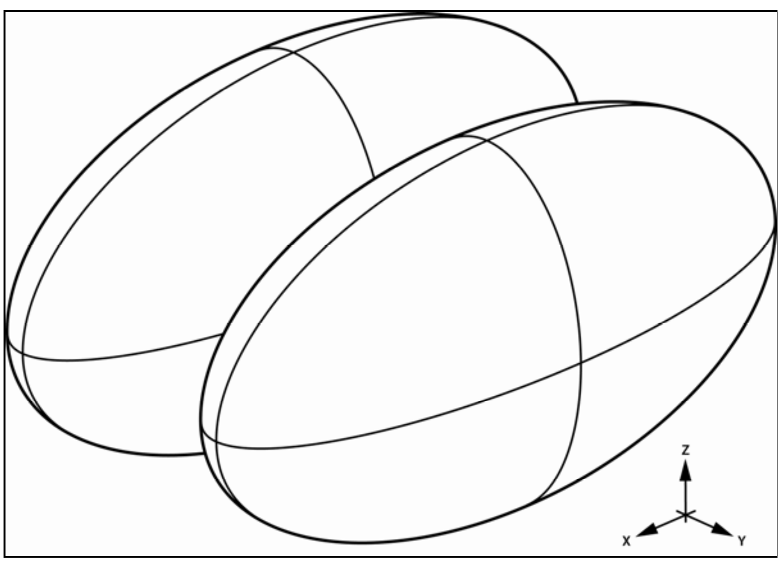

Figure 7. SAE J941 Three-Dimensional Tangent Cutoff Eyellipses for Left and Right Eyes (adapted from SAE, 2008)

Other research (Flannagan & Flannagan, 1998b) has indicated that the use of a method predicting, for a given vehicle, the size and location of the mirror adjustment range needed to accommodate a percentage of the anthropometric population may be a useful addition to determining accommodation for the total population. This method considers both the plan (horizontal plane) and side views of the eyellipse separately, and is based on degrees of horizontal and vertical adjustment past a reference line. This results in a rectangle showing accommodation based on vertical and horizontal adjustment of a mirror (Figure 8).

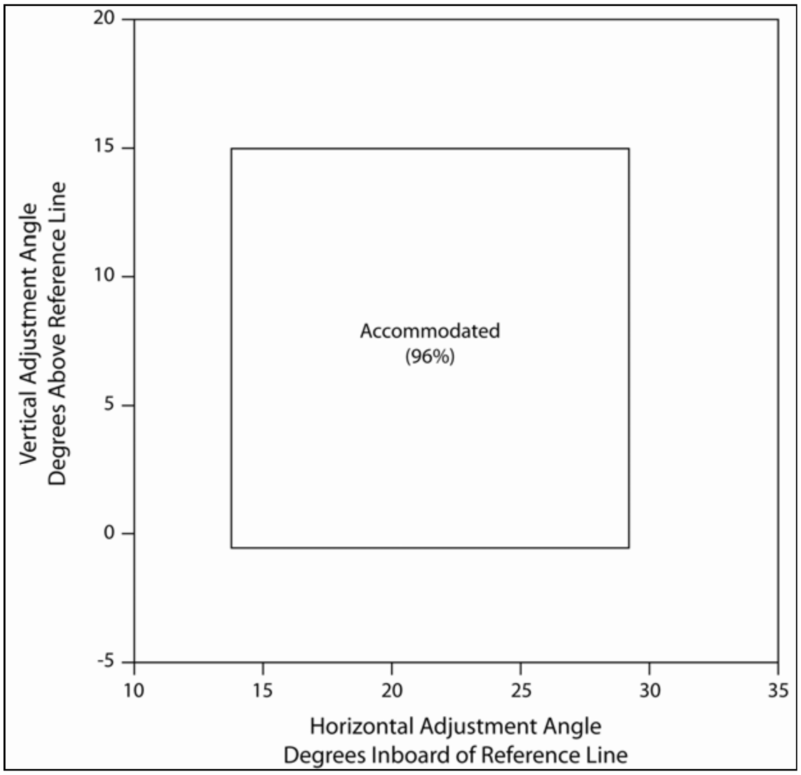

Figure 8. Mirror Adjustment Rectangle for 96 Percent Accommodation (adapted from Flannagan and Flannagan, 1998b)

Mirror Parameters

A rearview mirror may be described by several variables, including its ROC (including both the aspheric and convex portions), reflectivity, and reflectance. Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) provided a convenient method for the measurement of most basic planar and non-planar mirror parameters.

Radius of Curvature

The ROC, or geometric surface curvature, of the mirror is a measurement applicable to any non-planar mirror surface. The ROC is the distance from the center of curvature to the mirror surface. For a spherically convex mirror, the ROC is constant across the surface. For aspheric mirrors the ROC decreases across the horizontal dimension of the mirror, with the highest values at the portion proximal to the automobile body and the lowest values found at the portion distal to the automobile body. In comparison, a planar mirror has an infinite ROC.

The ROC of a convex mirror is measured, in accordance with §571.111, at 10 locations on the mirror surface. Two measurements are taken (at right angles) with a linear spherometer at the following locations: i) left and right ends of the horizontal line bisecting the mirror, ii) top and bottom ends of the vertical line bisecting the mirror, and iii) the center of the mirror. These 10 measurements (Figure 9) are averaged to determine the average ROC for the entire mirror surface. Additionally, the difference between each reading and the average ROC is calculated in order to determine the greatest percent deviation.

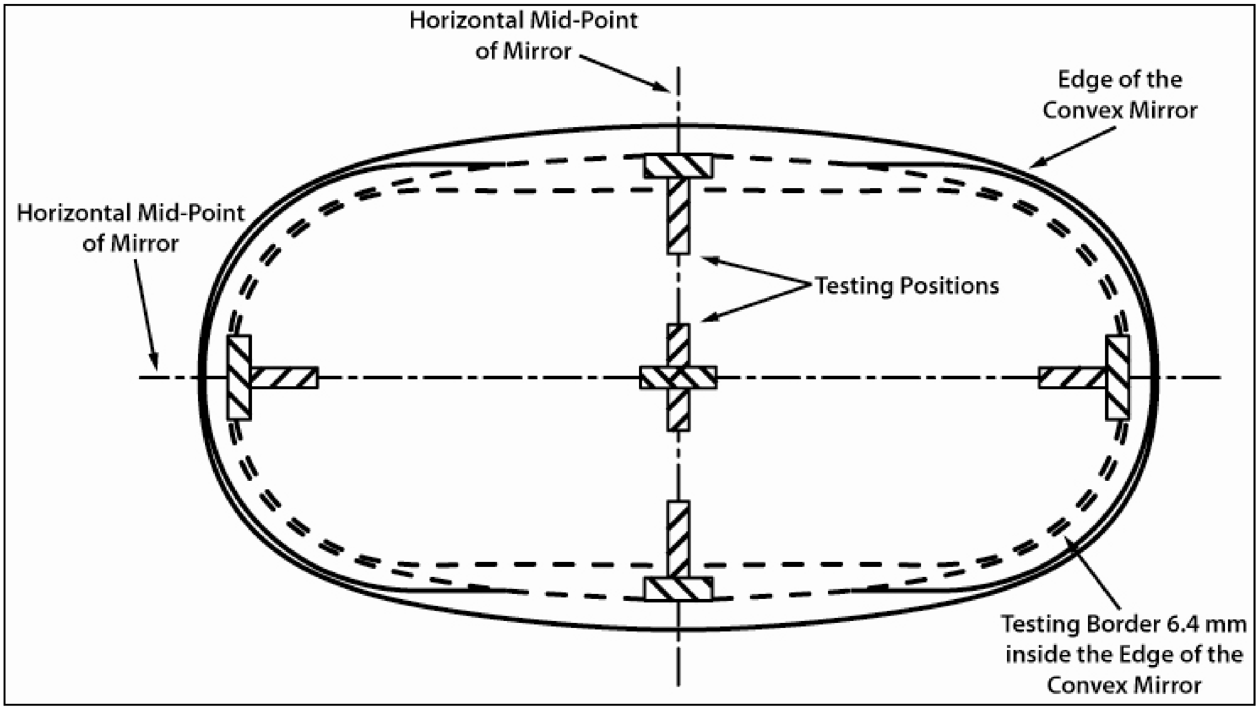

Figure 9. ROC Measurement Positions for a Convex Mirror (from Office of the Federal Register, 2002)

SAE standards for measuring the ROC of a convex mirror largely agree with U.S. DOT standards (J1246, 1982; reaffirmed 2003). In addition, procedures for determining ROC outlined in Wierwille et al. (2008) and Helder (1998) provide a method for estimating the ROC of a mirror through image analysis (using the size of the reflected image).

Reflectance and Reflectivity

Reflectance is the proportion of light returned from the mirror's surface (largely determined by the mirror reflecting material) and does not change based on mirror curvature. In contrast to this, reflectivity is a measure of proportion of light returned from a mirror's surface which is dependent on the mirror's reflectance and the ROC of the mirror. However, as noted by Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008), the reflectivity of an image in the aspheric section of a mirror will be diminished more than the same image appearing in a convex or planar mirror. This reduces the overall brightness of the image and reduces the amount of glare experienced. Wierwille et al. also note that while aspheric mirrors may have the same initial reflectivity as convex mirrors, the reflectivity tapers sooner with the decreasing ROC section. This results in aspheric mirrors having a larger FOV from which to reflect glare sources, however, and the glare produced will be at a much lower reflectivity.

Minification

Minification is a function of convex mirror surfaces where an image is rendered smaller than the size of the image would suggest. In non-planar mirrors, minification is the ratio of the virtual image's apparent size as compared to a planar mirror's virtual image for the same object in the same position. Image minification in convex mirrors is a function of both the object distance (distance between the object and the mirror) and the mirror's ROC. For a planar mirror, no relative minification occurs. Figure 10 presents the minification for a fixed object as a function of convex mirror ROC as compared to image size in a planar mirror. For a comprehensive discussion of minification, see Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, (2008).

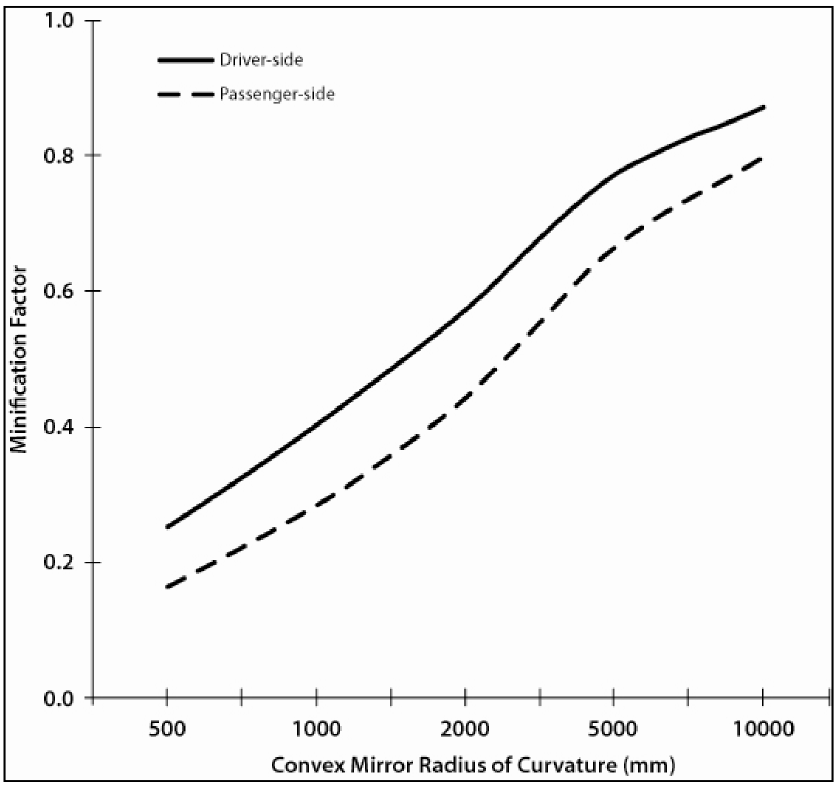

Figure 10. Minification as a Function of Mirror ROC (adapted from Wierwille et al., 2008)

LIGHT VEHICLE MIRROR TYPES

Planar

Planar, or flat/unit magnification, mirrors are those whose surface consists of a single plane. These mirrors reflect a virtual image that does not distort or minify the object size or distance of the object or surroundings. Current U.S. standards require the use of a planar mirror for use on the driver side and inside rearview mirrors.

Non-Planar

Two broad categories of non-planar mirrors exist: convex (spherical) and aspheric.

Spherical

Spherical, or convex, mirrors are curved towards the driver's eyes, and have the shape of a section of a sphere. These mirrors minify the virtual image by reducing the size of the image. However, by providing a diminished image, the spherical mirror provides a wider FOV as compared to planar mirrors.

Aspheric

Aspheric mirrors are complex mirrors combining a convex inner portion with an outer portion (termed the aspheric portion) that has a decreasing ROC (Figure 11). These mirrors provide a varying level of image distortion across the width of the mirror.

Aspheric mirrors provide each of the driver's eyes with a different image size. This has led to some concern that binocular disparity may be a problem in drivers' perception of objects through aspheric mirrors. Another concern is that drivers will attempt to judge speed and distance from the outer, diminishing ROC, section of the mirror (Pilhall, 1981). These concerns will be examined in the following sections. Similar to the properties of spherically convex mirrors, if the minification occurs to a greater extent across one axis (through a greater differential in ROC between horizontal or vertical axes), the image in the aspheric portion of the mirror will appear distorted.

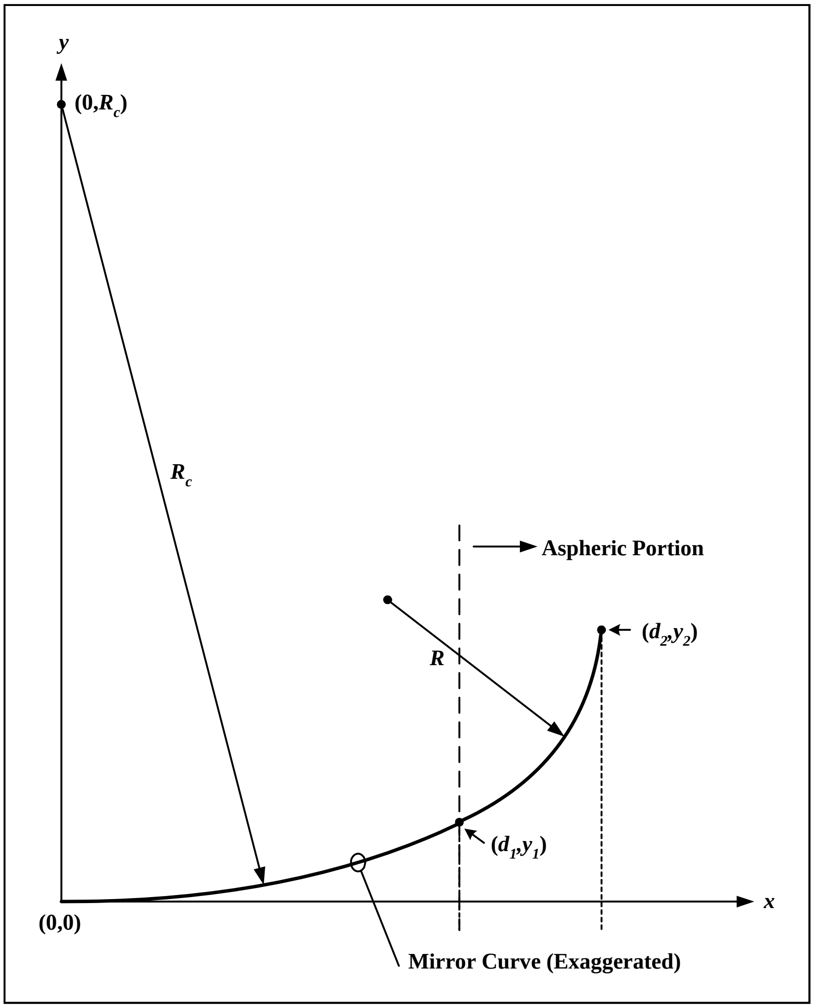

Figure 11. Coordinates of an Aspheric Mirror (from Wierwille et al., 2008)

Planar, spherically convex, and aspheric mirrors produce different images, even when the object is viewed from the same angle and position. A reference object (an International System, or SI, ruler) is shown in Figure 12, Figure 13, and Figure 14, viewed from the same focal length, aperture, viewing distance, and mirror (all of the same dimensions and position) and object position to demonstrate this. Note that, compared to the planar mirror (Figure 12), the convex mirror (Figure 13) and the aspheric mirror (Figure 14) both minify the image to some extent. However, the minification of the aspheric mirror becomes more pronounced in the section with decreasing ROC, occurring at the left side of the mirror.

Figure 12. Reference Object Viewed Through a Planar Mirror

Figure 13. Reference Object Viewed Through a 1400 mm ROC Spherically Convex Mirror

Figure 14. Reference Object Viewed Through a 1400 mm ROC Aspheric Mirror (15 Percent Outboard Aspheric, 85 Percent Inboard Spherically Convex)

SUMMARY

Two broad categories of light-vehicle exterior rearview mirrors are in common use: planar and non-planar. The non-planar mirrors may be further divided into categories of convex and aspheric mirrors. Both forms of non-planar mirrors provide a minified image that is reduced in size as compared to an image provided through a planar mirror. Current U.S. regulations provide for the use of a planar mirror on the driver side of a vehicle and allow for convex non-planar mirrors on the passenger side. United Nations Economic Commission for Europe (U.N. ECE) regulations allow the use of both types of mirrors on the driver side of a light vehicle.

CHAPTER 3. MIRROR CONFIGURATION

FRAME SIZE AND SHAPE

In planar mirrors, the FOV is the outcome of the distance between the driver's eye and the mirror display, the aim and orientation of the mirror, and mirror dimensions. Closer viewing distances (reductions in the distance between the mirror surface and the driver's eye) and greater overall size of a non-planar mirror all lead to increased FOV. Non-planar mirrors add the additional factor of the mirror's convexity (expressed in terms of the mirror's ROC) to this relationship. Decreases in a mirror's ROC results in an increase in convexity. This increases the FOV provided by the mirror, but at the same time increases the image minification.

Federal regulations do not directly specify the size or shape of light vehicle rearview mirrors. Instead, a minimum FOV for the driver is specified. FMVSS 111 provides for a 2.4 m wide field at a position 10.7 m behind the driver's eye point. This is to be achieved through the use of a planar mirror on the driver side. A convex mirror (with a ROC between 889 and 1651 mm) is allowed on the passenger side. This requirement, combined with the viewing distance between the driver's eye and mirror, aim of the mirror, and dimensions of the mirror, determine some minimum sizes possible for passenger vehicle mirrors.

Specifications for minimum mirror size have been determined. Seashore and Lundquist (1968) examined various mirror applications and provided a set of guideline recommendations for commercial-use light vehicles. They determined that, while planar mirror applications were needed to allow for accurate and precise judgments of surrounding traffic, supplementary convex mirrors would allow drivers to see into the blind spots around the vehicle. However, due to image minification and the distances drivers' eyes are from the mirrors, larger surface areas were needed for the additional convex mirrors. For light trucks and vans, the authors recommended equally sized planar and convex mirrors, with each mirror section having an area of approximately 129 cm^2. In this configuration, the planar mirror (10.16 cm by 12.7 cm) is positioned above the equally dimensioned convex mirror. The two mirror sections were separated by approximately 5 cm, allowing for some degree of forward vision through the mirror housing. This combination mirror is in common use on heavy vehicles (Spaulding, Wierwille, Gupta, & Hanowski, 2005).

The head movements associated with mirror sampling are an important factor in rearview mirror design, as more exaggerated head movements require more time to complete and increase the amount of time a driver's attention is away from the forward roadway. Bhise, Meldrum, Jack, Troell, Hoffmeister, and Forbes (1981) studied driver head movements related to the use of passenger-side rearview mirrors in lane-change maneuvers. Drivers were asked to execute lane changes, using mirrors of different widths, both with and without a vehicle approaching from the rear adjacent travel lane. The four mirrors examined are detailed in Table 1.

Table 1. Four Mirror Configurations Examined in Bhise et al., 1981

Mirror Width (in cm)	Mirror Height (in cm)	Total Mirror Area (in cm^2)
6.0	8.1	48.6
13.0	8.1	105.3
19.9	8.1	161.2
26.9	8.1	217.9

The results of Bhise et al. (1981) indicated that drivers' head movements were significantly influenced by not only traffic conditions, but also by the rearview mirror width. When oncoming traffic was present in an adjacent lane, drivers made smaller lateral head movements (by approximately 1.27 cm) and increased the duration of their mirror glances (by an average of 0.25 s) as compared to conditions with no oncoming traffic in the adjacent lane. Likewise, when smaller width (6.0 and 13.0 cm) mirrors were used, drivers made larger head movements. The wider mirror widths (19.9 and 26.9 cm width mirrors) allowed drivers to make smaller head movements to adequately sample information from the adjacent lane. Mirror width did not, however, demonstrate an effect for the duration of glances to the mirror. The authors did indicate that large individual differences were present in mirror glance behavior, with many drivers seeking information from either interior rearview mirrors or by using full head turns for direct viewing of the adjacent lane.

It is also possible to use mathematical calculations to determine size requirements for rearview mirrors. Seeser (1976) used different assumptions on FOV requirements of the driver, and calculated appropriate planar rearview mirror sizes for each. Seeser's analysis accounted for head position, mirror orientation, and head rotation for a 2-mirror system (driver side and interior rearview mirror). In general, a head turn of approximately 27 degrees would need a horizontal rearview mirror size of approximately 19 cm to adequately obtain information about targets. Note that this head turn is well within SAE standards for an easy head movement (45 degrees horizontal). In addition, Seeser identified an inverse relationship between driver side rearview mirror size and the angle of head turns needed to obtain information from the mirror. As mirrors are made larger, the head turns required to accurately sample information from the mirror decrease.

Burger, Mulholland, Smith, Sharkey, and Bardales (1980) performed a series of on-road lane-change experiments examining the use of planar, convex, and aspheric mirrors. In addition to different mirror types, differing vertical sizes of mirrors were examined. The results indicated that mirrors with a vertical dimension between 7.6 and 8.9 cm would have the greatest effect on drivers' ability to quickly and accurately obtain information from the mirror. As the authors found that the 1400 mm ROC convex mirror resulted in the highest FOV for drivers, the ideal horizontal dimension for this mirror was determined to be between 16.5 to 17.8 cm. Burger et al.

did note that extreme convexities (such as a 508 mm mirror tested in this study) approached the tolerable limit of perceptual distortion which drivers would accept.

Flannagan and Sivak (2003) reported the results of an experiment examining frame size on distance perception. Participants performed a distance judgment task in a stationary, parked vehicle using either the interior or exterior rearview mirror. Both rearview mirrors were planar. Participants were asked to make a relative judgment (using the distance to a vehicle parked in front of the participant's vehicle as a value of 100 units) of the distance to a test vehicle behind the participant at one of four positions (20, 30, 40, and 50 m) in the adjacent lane. Participants were only allowed to use either the interior or side rearview mirror to make their judgment. The results indicate that frame size did not affect the participants' judgment of distances.

Sivak, Devonshire, Flannagan, and Reed (2008) examined the effect of driver side rearview mirror size on lane-change collisions through crash records. Data from 77 light vehicles (37 passenger cars, 14 minivans, 14 sport-utility vehicles, and 12 light trucks) were obtained, with variables including mirror location, mirror width, mirror height, total mirror area, and vehicle identifying information (year, make, model). FOV was measured using both estimations of maximum FOV based on driver eye points in the seated position and a target detection task with the driver seated in his or her vehicle. Data from these vehicles were extracted from 1991-2005 North Carolina crash data, and crash frequencies for vehicle crashes (lane change and merge, going straight ahead) were calculated for each of the 77 vehicle types. Mirror width, height, calculated FOV, effective FOV, and vehicle weight were compared to the ratio of lane change and merge collisions to going-straight-ahead collisions. Although some expected correlations were present between factors such as the width and height of mirrors, and between vehicle weight and both mirror width and height, there was no statistical relationship between mirror size (width or height) and lane-change crashes. Interestingly, while a significant correlation between mirror width and the nominal (mathematically derived) FOV was present ($r = .42$, $p \leq .01$), no significant correlation between mirror width and the effective (determined through the target detection task) FOV was present ($r = .04$, n.s.). Likewise, a follow-up analysis demonstrated no correlation between nominal and effective FOV ($r = -.02$, n.s.). This may be seen as evidence that the maximum FOV provided by a rearview mirror is not always used by the driver. Factors such as mirror adjustment and seating position (determining the eyellipse driver eye position) can negate much of the increase in FOV that an optimized mirror may provide.

An observational experiment conducted by Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) examined the mirror adjustment strategies of 25 drivers in their own vehicles. Drivers were asked to sit in their personal vehicle with the window down while FOV measurements were obtained. Drivers were not allowed to make adjustments to their mirrors prior to measurement in an attempt to obtain the true driver-adjusted rearview mirror FOV. The results demonstrated that the average FOV provided by the exterior rearview mirror on the driver side was 12.6 degrees ($SD = 2.6$). Drivers' direct vision (obtained from a full head turn) had an average of 58.8 degrees ($SD = 12.1$). This is a larger value than the 45 degree estimate commonly used (Flannagan, Sivak, & Traube, 1999), and suggests that the blind spot area may be larger than is commonly believed due to drivers' actual mirror adjustment.

Reed, Lehto, and Flannagan (2000) measured the FOV of 43 drivers' personal vehicles. FOV measurements were obtained using a pole-sighting technique as well as through 3-dimensional measurement using a computerized measurement device. Results indicate that drivers had an average horizontal FOV of 12.9 degrees for the left (driver side), 25.3 degrees for the center rearview, and 22.5 degrees for the right (passenger side) mirrors. This wound up producing an average visual area of 14 degrees from the driver side and 19.8 degrees from the passenger side of the vehicle. No differences in mirror alignment and FOV were found for driver age, sex, or body size. Most drivers were aligning their mirrors with the vehicle's body as a defining edge to the mirror FOV and, on average, the vehicle occupied 21 percent of the driver-side mirror's available FOV.

Some evidence suggests that increasing the horizontal FOV of a planar mirror does not lead to changes in drivers' mirror-sampling behavior. Mourant and Donohue (1974) examined the effect of mirror dimension on sampling behavior. While they drove, drivers' eye movements were monitored using two planar mirror systems (a baseline mirror and one with a 25 percent greater FOV for the left rearview mirror). Drivers performed straight line driving, merges, and lane-change maneuvers. Results indicated that the increased FOV provided by a wider planar mirror did not lead to changes in the number of glances or the duration of glances required by drivers.

The size and shape of an aspheric mirror, by necessity, involves both the dimensions of the spherical (convex) inner portion and the aspheric (decreasing ROC) outer portion. Increasing the linear width of the aspheric portion of a mirror holds the promise of increasing the driver's FOV. However, this may occur at the expense of the accuracy of driver judgments through the mirror. In the process of reviewing available literature, little work specifically examining the proportion of spherical to aspheric sections was identified. One such study examining differences in this proportion with aspheric mirrors was reported by Flannagan and Flannagan (1998a). As part of an experiment examining driver acceptance of non-planar mirrors, Flannagan and Flannagan examined aspheric mirrors with three different variable ROC areas. The small, medium, and large variable area mirrors had 34, 40, and 66 percent of total mirror width variable radius area comprised of the aspheric section, respectively. Although theoretically providing the largest FOV for drivers, the aspheric mirror with the large (66 percent) variable radius area had an actual FOV (determined through a target detection task) lower than that of the other aspheric mirrors. This is likely due to the number of drivers who adjusted their mirrors to have the side of the vehicle in view of the mirror. Likewise, the large variable area mirror had a lower overall subjective preference from drivers, as compared to both the small and medium variable radius area mirrors. The small and medium variable radius area mirrors had a larger effective (driver adjusted) FOV, and were accepted as comfortable to use by drivers more rapidly, as compared to the larger area.

In a test track examination of aspheric mirrors, Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) studied planar, convex (1400 and 2000 mm ROC), aspheric (1400 mm ROC with a 73 percent spherically convex inner portion, and 2000 mm ROC with a 66 percent spherically convex inner portion), and elongated flat and convex mirrors. The elongated mirrors were chosen in order to support better distance estimation though additional optic flow information, with the assumption that gap acceptance would be affected by this increase in distance estimation performance. Participants were asked to make a passing maneuver using one of the experimental mirrors, and mark the last acceptable gap through a button press. No significant differences were found between any of the mirror types for eye-glance patterns. There was a significant difference in gap acceptance based on mirror type.

Although the elongated planar mirror produced the largest (safest) gaps accepted, all of the mirrors tested produced average gaps within 2.35 m of one another.

Minimizing head movements, in addition to eye movements, will help reduce eyes-off-road time. This can be achieved through optimal mirror placement. Walraven and Michon (1969) examined the placement of mirrors in passenger cars. A circular mirror with a 125 mm diameter was mounted in one of three positions on a test vehicle. These mounting positions resulted in the mirror being at 12, 18, or 36 degrees laterally from the driver's forward line of sight. The participants in the study drove the vehicle while performing a target detection task (attempting to view a target lamp mounted at the rear of the vehicle which would light intermittently). Reaction time and eye movements were recorded, and results indicated that a mirror position approximately 18 degrees from the centerline resulted in the lowest reaction time. This finding supported earlier recommendations suggesting that the driver exterior rearview mirror should be positioned within approximately 30 degrees from the forward line of gaze (Morrow, 1962).

SUMMARY

Although planar mirror size and shape has been extensively studied, little comparative work specifically examining aspheric mirrors has been performed. When examining the research dealing with all non-planar mirror configurations (including convex mirrors), it is possible to make some determinations on the optimum size and shape for a convex mirror. However, drawing firm conclusions regarding the appropriate size and shape for an aspheric mirror, with its more complex surface and additional issues such as ratio of inner and outer portions, is not appropriate. Two studies which specifically examined aspheric mirror size provided some complementary findings. Drivers did not prefer a large decreasing radius section of an aspheric mirror (Flannagan and Flannagan, 1998a), and the overall size of the mirror had little practical effect on lane-change behaviors (Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008). However, the overall findings suggest that mirror size does not have a direct relationship to driver performance, and that more work is needed to draw conclusions regarding the relationship between configuration of a non-planar mirror and driver performance. Summaries for the literature findings are provided in Table 2.

Table 2. Summary of Mirror Configuration Findings

Reference	Finding
Seashore & Lundquist (1968)	Larger sizes of non-planar rearview mirrors are needed to produce image sizes equivalent to planar mirrors.
Walraven & Michon (1969)	Rearview mirrors are ideally placed approximately 18 degrees from the centerline.
Mourant & Donohue (1974)	Increases in FOV provided by a wider mirror do not lead to changes in driver eye behavior.

Seeser (1976)	Mathematical determination of mirror size from FOV requirements. There is an inverse relationship between mirror width and head turn angle.
Burger, Mulholland, Smith, Sharkey, & Bardales (1980)	Vertical dimensions between 7.6 and 8.9 cm, and horizontal dimensions between 16.5 to 17.8 cm, have the greatest effect on driver ability to quickly sample mirror information. A 1400 mm ROC convex rearview mirror was found to be the ideal convexity of all mirrors tested.
Bhise, Meldrum, Jack, Troell, Hoffmeister, & Forbes (1981)	Larger mirror widths require smaller head movements, but do not change visual fixation duration. Higher density traffic conditions result in smaller head movements and longer visual fixations.
Flannagan & Flannagan (1998a)	Driver rearview mirror adjustments negate possible benefits to larger aspheric (variable ROC) curvature areas.
Flannagan & Sivak (2003)	Framing size does not affect distance judgments.
Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski (2008)	Drivers have an average FOV from the driver side exterior rearview mirror of approximately 12.6 degrees. Blind spots may be larger than commonly believed. Elongated (increased height) mirrors can produce a small, but significant, increase in accepted gap size.
Sivak, Devonshire, Flannagan, & Reed (2008)	There is not a correlation between mirror width and effective (driver adjusted) rearview mirror FOV. There is no correlation between mirror dimensions (width or height) and lane-change collisions.

CHAPTER 4. HUMAN PERFORMANCE WITH NON-PLANAR MIRRORS

INTRODUCTION

Human performance issues of rearview mirrors have typically been assessed through laboratory testing, testing with a driver in a stationary vehicle (with either moving or stationary targets), and on-road testing (through test track and naturalistic observation data collection). These studies have, for the most part, relied upon the driver-participant performing target detection tasks or performing lane-change maneuvers. Some laboratory and stationary-driver testing experiments have asked participants to make judgments of distance to a target (such as a vehicle) and provide either relative or absolute judgments of distance. In addition to performance measures such as reaction time, distance judgment error, and gap judgment, eye-glance behavior has proven to be an important measure. This highlights the importance of visual information processing in rearview mirror use.

Bascunana (1995) studied the characteristics of safe versus unsafe lane-change maneuvers. The dynamic conditions defining a safe lane change are primarily the relative distances and velocities between vehicles at initiation of the lane change, and the geometry of the lane-change maneuver (e.g., the collision path). Both of these judgments require the driver to accurately sample information from the vehicle rearview mirrors. There is a strong relationship between visual information processing (such as mirror sampling behaviors) and crash involvement (Avolio, Kroeck, & Panek, 1985). Understanding how drivers obtain information from exterior rearview mirrors, and how this sampling process affects driver decisions, has practical implications for the design and optimization of mirrors. Mirror sampling has been extensively examined over the past decades, yielding a tremendous amount of information on driver performance.

In an early study of mirror sampling in driving, Mourant and Rockwell (1972) recorded eye behavior while drivers traversed a neighborhood (3.4 km) and freeway (6.9 km) route. Participants included both novice and experienced drivers who had eye glance and mirror sampling recorded as they completed turns, lane changes, and merges. Analysis indicated that experienced drivers make more fixations on the exterior rearview mirror, and have longer average glance durations for the exterior rearview mirror, as opposed to novice drivers. However in a later study with a similar method examining a smaller number of drivers in multiple age ranges, Mourant and Donohue (1977) determined that experience was positively correlated with the number of glances but was independent of the glance duration. These findings indicate that novice and beginning drivers may have some degree of difficulty in accurately sampling information from a vehicle's exterior rearview mirrors. Likewise, eye movement studies of drivers merging onto highways have indicated that drivers begin sampling exterior rearview mirrors well before reaching the merge/closure point (Bhise, 1973).

Drivers typically sample mirrors more frequently during lane-change maneuvers, with sampling for a left lane change requiring more total time than a right lane change (Mourant & Donohue, 1974). Yet, the time required for drivers to sample information from a mirror varies considerably. Taoka (1990) lists average values for sampling information from several in-vehicle displays. The left exterior rearview mirror had a mean glance duration of 1.10 s (*SD* = 0.30, 5th Percentile = 0.68 s, 95th Percentile = 1.65 s), while the interior rearview mirror had a mean glance duration of 0.75 s (*SD* = 0.36, 5th Percentile = 0.32 s, 95th Percentile = 1.43 s). Clearly, drivers demonstrate considerable spread in their sampling characteristics, making the optimization of vehicle mirrors a priority.

This finding of greatly variable performance has been confirmed in naturalistic observation studies. Lee, Olsen, and Wierwille (2004) recorded 16 drivers for 10 days each (generating a total of approximately 38,600 km of driving and 8,667 lane changes observed). The results provide very informative information regarding drivers' lane changing behavior. Most lane changes (55 percent) are to the left. Lee et al. indicate that most left lane changes were passing maneuvers, where drivers were passing a slower lead vehicle. These lane-change maneuvers took longer to execute as compared to right lane changes (11.1 s versus 6.6 s for left and right lane changes, respectively). Follow-up analysis examined eye-glance behaviors. The results of this analysis indicated that the highest probability for eye glance is on the forward roadway. Left and right lane changes have left and right rearview mirror glance probabilities of .52 and .21, respectively (Table 3). Interesting, the authors indicate that 95 percent of drivers accept gaps of approximately 12 m forward and back, closing rates of under approximately 6 m/s, and Time to Collision (TTC) of between 4 and 6 s when beginning a lane-change maneuver. These results can provide context for the assessment of potential benefits from non-planar rearview mirrors.

Table 3. Glance Probabilities During Lane Changes (from Lee, Olsen, & Wierwille, 2004)

Lane Change Direction	Forward Glance Probability	Interior Rearview Mirror Glance Probability	Exterior Rearview Mirror Glance Probability
Left	1.0	0.52	0.52 (left mirror)
Right	1.0	0.55	0.21 (right mirror)

Ayres, Li, Trachtman, and Young (2005) assessed the benefits provided by passenger-side rearview mirrors in a lane-change scenario. Participants drove an instrumented vehicle on a test route of approximately 10.5 km and they were asked to make both left and right lane changes while their eye and head movements were recorded using dash-mounted cameras. Participants looked at the inside rearview mirror during 97.5 percent of rightward lane changes. However, the passenger-side mounted rearview mirror was used in only 65% of rightward lane changes. Large individual differences were noted in mirror scanning behavior; however, these may be explained by the relatively small sample size. Additionally, individual differences in rearview mirror use were indicated by the variations in drivers' self-reported use of the exterior rearview mirror during rightward lane changes.

DETECTION, IDENTIFICATION, AND ESTIMATIONS

Mourant and DeNald (1974) measured reaction time in a decision and recognition task while participants viewed stimuli through planar and convex mirrors. Drivers sat in a stationary vehicle while responding to the presence and orientation of Landolt rings viewed through three types of mirrors (planar, 1016 mm ROC convex, and 1524 mm ROC convex). There was a significant effect for mirror type on reaction time. Drivers' average reaction time to the stimuli increased as the mirror moved from planar, to 1524 mm ROC convex, to 1016 mm ROC convex. Likewise, a significant effect for mirror type on detection of orientation was present. Drivers had the lowest detection time with planar mirrors, followed by the 1524 mm ROC mirror. The longest detection time was obtained from the mirror with the highest convexity, the 1016 mm ROC mirror.

Sugiura and Kimura (1978) reported findings from a stationary-driver experiment examining distance, speed, and motion perception judgments. Six mirrors were used in these tests: a planar mirror and convex mirrors with ROCs of 300, 600, 900, 1200, and 1500 mm. Participants were asked to perform judgments while either viewing stimuli through the test mirrors while a target car was at a fixed position (for estimates of distance) or while viewing films in which a vehicle approached from the rear (for estimates of speed, motion perception). The findings indicated that participants typically overestimated the distance to a target when using convex mirrors, and that this effect was magnified as the convexity of a mirror increases. Planar mirrors tended to produce underestimations of distance. For speed judgments, participants tended to overestimate approach speeds at lower actual speeds and, as approach speeds increased, their estimation accuracy improved. This overestimation was especially exaggerated with the smallest ROC mirrors (300 mm and 600 mm). Likewise, motion perception was hindered as the curvature of the mirror is increased; motion perception performance using the 300 mm mirror was only 40 percent as accurate as judgments made through a planar mirror. The authors concluded that a convex mirror with a 900-1200 mm ROC is the ideal, as this size represents an optimized tradeoff between supporting judgments of distance, speed, and motion, and providing an adequate FOV. It is important to note that some researchers (Smith, Bardales, & Burger, 1978; Burger, Mulholland, Smith, & Sharkey, 1980) have determined language translation errors in this paper which changed the direction of findings. Examination of the formulas used and the results table reveal that drivers were actually underestimating distances and speeds, and that the effects were magnified by decreasing ROC mirrors. This greatly changes the findings of the paper, brings the findings into accord with other research, and gives stronger support to the authors' conclusion of ideal mirror convexity. The findings discussed here were presented with consideration of this correction.

Mourant and Donohue (1979) examined mirror scanning behavior with drivers using convex (1016 mm ROC) and planar right rearview mirrors. Drivers' eye behavior was measured as they executed lane changes on a fixed route on public roads. Results indicated that convex mirrors allow drivers to reduce the number of fixations required on the mirror while executing a lane change. An additional finding was that the addition of a non-planar right rearview mirror did not affect the mirror sampling behavior from the left planar rearview mirror. Thus, drivers using convex and planar mirrors on the same vehicle did not appear to incur difficulties in adapting to the mixed system.

Burger, Mulholland, Smith, and Sharkey (1980) conducted a series of stationary-driver tests to examine gap acceptance, speed, and distance judgment performance using different mirror configurations and mirror types. Participants in this study were positioned in a stationary vehicle and viewed an oncoming target vehicle through a convex mirror with a ROC of either 508, 1016, 1397, or 2032 mm. The stimulus vehicle traveled towards the participant's vehicle at a set speed and path. Participants were asked to provide distance judgments and minimum acceptable gap judgments (simulating a lane-change maneuver), as well as subjective feedback on the mirrors. When comparing absolute distance errors (which did not consider the direction of the error, only the total amount of error), there were no differences between the various ROCs, except for the

508 mm ROC mirror (which produced a larger absolute distance error). When examining the relative distance error (which took the direction, either over- or underestimation into account), the two smaller ROC mirrors (508 and 1016 mm) produced overestimations, while the larger ROC mirrors produced underestimates (Figure 15). These participants tended to underestimate distance when using planar mirrors.

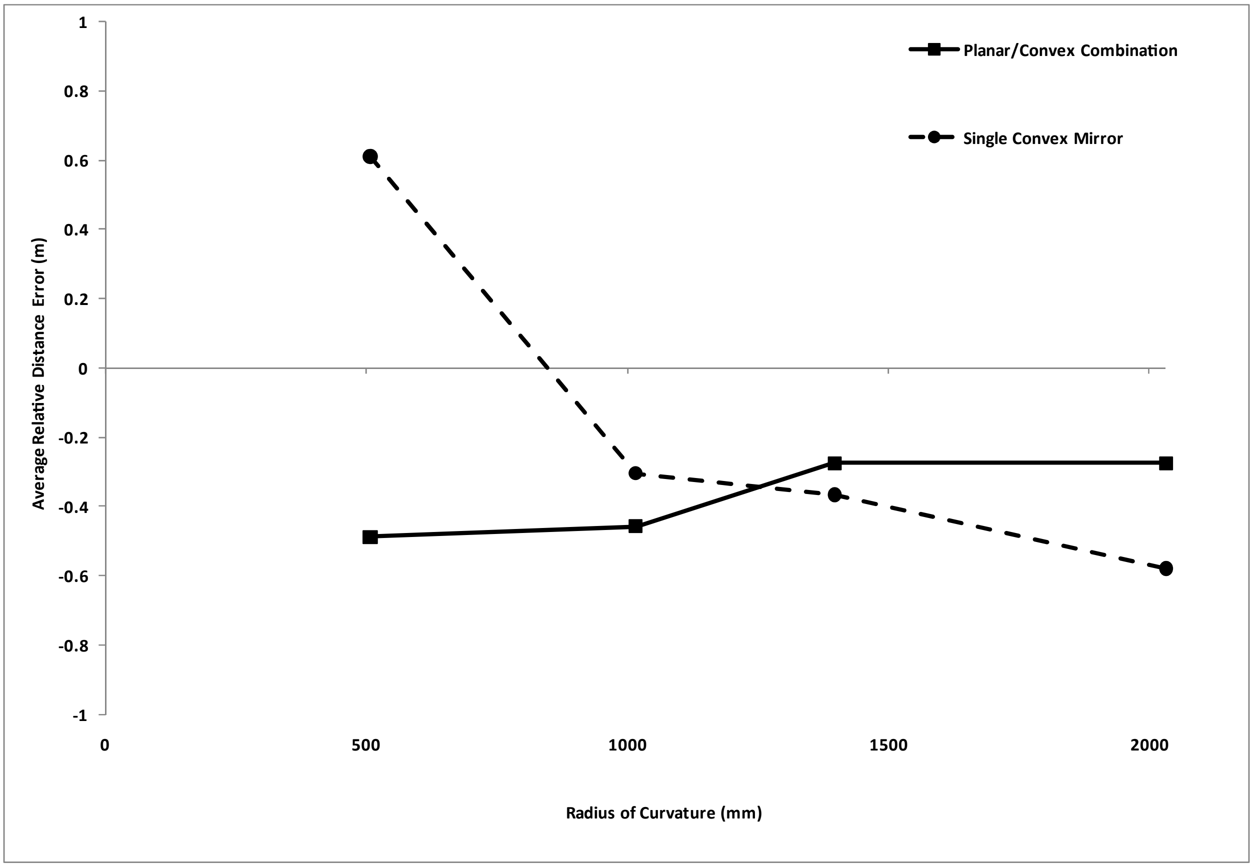

Figure 15. Relative Distance Error by Mirror Type (adapted from Burger, 1980)

In a laboratory experiment, Fisher and Galer (1984) investigated the effects of various ROC mirrors on distance judgments. Participants were presented with a motion picture of oncoming traffic that had been filmed through mirrors with different ROCs. The mirrors used to produce the stimuli included a planar mirror and non-planar mirrors with ROCs of 600, 1400, and 1950 mm, respectively. The films consisted of a target vehicle approaching the viewpoint of the observer at speeds of 72, 80, and 97 km/h, and the presentation ended at a TTC of approximately 2.5 s. Participants were asked to mark the last safe gap that they would accept for a lane-change maneuver. The results indicated that as the ROC of the mirror was reduced, the gaps accepted by participants became smaller. This effect was magnified by greater approach speeds.

In a laboratory experiment, Helmers, Flannagan, Sivak, Owens, Battle, and Sato (1992) examined choice reaction time (reaction time judgments where multiple response options are present) for participants viewing an image of a vehicle presented through planar, convex (2100 mm ROC), and aspheric (2100 mm ROC convex section) mirrors. Results indicate that the longest reaction times were when participants used the planar mirror, followed by the convex (Figure 16). The lowest reaction time was obtained from the 2100 ROC aspheric mirror. Interestingly, while the number of incorrect responses (such as a participant giving a false alarm to a scene with no vehicle present) was very low (under 2 percent), the number of incorrect responses was approximately twice as high for participants with the convex mirror as compared to either the planar or aspheric mirror.

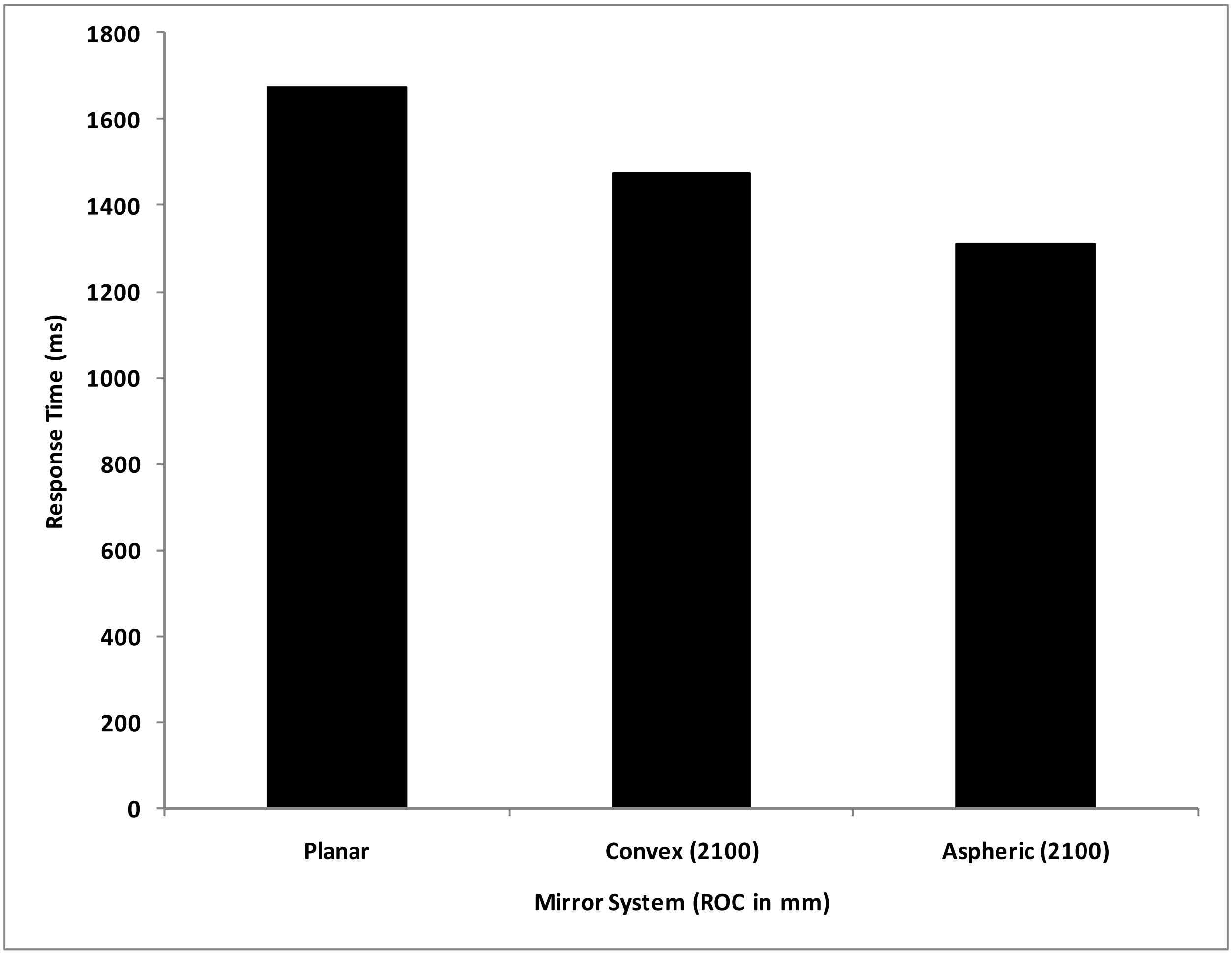

Figure 16. Response Time by Mirror Type (adapted from Helmers et al., 1992)

One of the earliest studies examining driver performance issues with non-planar mirrors in a moving vehicle was conducted by Bowles (1969). This study observed drivers performing a gap acceptance passing maneuver on a 3-lane freeway, and was conducted using four different exterior rearview mirror configurations. Drivers followed a lead vehicle as a confederate vehicle approached from behind in the adjacent lane. Drivers received a signal to make a lane change once the rearward approaching vehicle reached a set distance from the driver. Both planar and convex (approximately 1219 mm ROC) mirrors were examined in both fender and door mounted positions, varying both the mirror type and the effective size of the image produced. A main effect for the mirror type (planar versus convex) was found; drivers using the convex mirrors accepted significantly smaller gaps as compared to gaps accepted using the planar mirror. No difference was found for gap acceptance based on mirror mounting position. Although no statistical differences were found for go/no-go lane-change response time based on mirror type, a pattern of drivers taking longer to make a judgment through convex as compared to planar mirrors was present. Increased power in this study may have led to significance being reached.

Mortimer and Jorgeson (1974) reported the results of a study examining the effect of two rearview mirrors (a planar and a 1200 mm convex) in a car-overtaking task in both day and night conditions. Participants were asked to perform a lane change and passing maneuver while a confederate vehicle approached inside the passing lane from behind. The participant driver was following the lead vehicle and traveling at 72 km/h and the speed of the approaching vehicle was set at either 11 or 24 km/h faster than the participant driver was traveling. Results indicate that there were no differences in the average gaps accepted between trials using the convex and planar mirrors, nor were there differences in gaps accepted due to lighting (day or night). Likewise, probability of collisions (calculated using the outcome if the driver of the following vehicle had not taken an evasive maneuver) indicated no significant differences between collision probabilities based on mirror type. Drivers did use the planar exterior mirror more frequently (in terms of glances and duration of glances to the mirror) as compared to the convex mirror.

In a follow-up to their earlier testing (reported in Burger, Mulholland, Smith, & Sharkey, 1980), Burger, Mulholland, Smith, Sharkey, and Bardales (1980) compared planar mirrors against convex mirrors with ROCs of 1016 and 1397 mm in an on-road test. These two mirrors were identified as having an optimal ROC in prior stationary-driver testing. The authors recorded eye-glance time and frequency while drivers completed lane changes on-road. In addition, the minimal safe gap (i.e., below approximately 18 m) was defined by the experimenters and analyzed. Results indicated no effect of mirror convexity on the number of unsafe gaps accepted. However, there was a significant effect for direction of the lane change. Regardless of mirror convexity, right lane changes had approximately double the number of unsafe gaps accepted as compared to left lane changes. The authors concluded that, even with convex mirrors, significant blind zones were present on the right side of the vehicle. Eye-glance behavior did not significantly differ for left lane changes. For right lane changes, increased FOV provided by the convex mirrors reduced the required frequency and duration of glances. The authors concluded that the 1397 mm ROC convex mirror provided the ideal FOV, resulted in the highest level of driver performance, and was subjectively preferred by the participants.

A study by De Vos (2000) examined planar, spherically convex (1400 mm ROC), and aspheric mirrors (1400 and 2000 mm ROC; both of approximately 75 percent spherical inboard and 25 percent aspheric outboard sections) in a gap acceptance task. Participants using the experimental mirrors drove on a closed test track while a vehicle approached from the rear and marked the smallest point with an acceptable gap for a lane-change maneuver into the adjacent lane. Gaps accepted for the non-planar mirrors were all significantly smaller (less safe) as compared to gap acceptance using the planar mirror (Figure 17). The 2000 mm ROC aspheric mirror produced average gaps which were greater than the 1400 mm convex and aspheric mirrors, but this difference did not reach significance.

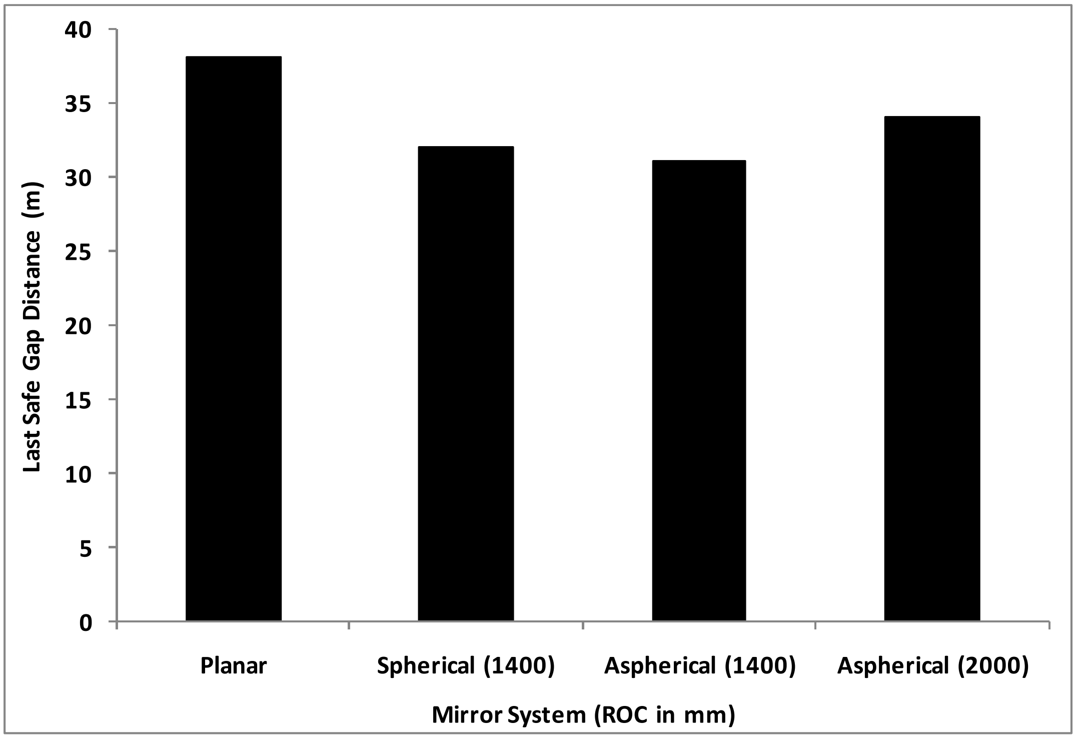

Figure 17. Last Safe Gap Accepted by Mirror Type (adapted from De Vos, 2000)

Some findings have indicated that experience using non-planar mirrors does not offset a difference in gap acceptance. In an on-road study, De Vos, Van der Horst, and Perel (2001) examined lane change/gap acceptance performance for drivers using either planar or non-planar (including a 1400 mm ROC spherically convex mirror, and two aspheric mirrors with ROCs of 1400 and 2000 mm, respectively) mirror configurations. Both aspheric mirrors consisted of approximately 75 percent spherically convex inner portions and 25 percent aspheric outer portions. The experimental task consisted of the driver traveling on a course while a confederate vehicle approached from behind in an adjacent lane. The driver was asked to indicate the last safe gap that they would accept. Results indicate that mirror type had a significant influence on gap acceptance. Driver minimum acceptable gap was significantly larger (safer) while using planar mirrors as compared to all non-planar mirrors. No differences in gap acceptance was found for the non-planar mirrors. While no main effect was present for the type of mirror participants had on their personal automobile, there was a significant interaction for their personal automobile mirror type and the experimental mirror used in the task. This interaction was present as drivers whose personal automobiles were equipped with convex mirrors maintained larger acceptable gaps as compared to participants with personal automobiles equipped with either planar or aspheric mirrors. This finding appears to indicate drivers may have difficulty adjusting from planar and aspheric mirrors to spherically convex mirrors.

Staplin, Lococo, Sim, and Gish (1998) describe a simulator-based experiment examining the use of different mirrors in lane-change maneuvers. Five different exterior rearview mirror types were examined as drivers completed the lane-change tasks. Experimental mirrors consisted of a planar mirror, a 2032 mm ROC convex mirror, a horizontally split mirror with an upper planar section and a lower section consisting of a 635 mm ROC convex surface, a vertically split aspheric mirror with 40 percent of the inboard area comprised of a 2794 mm ROC convex section and a 60 percent aspherical outboard surface section, and a vertically split aspheric mirror with 75 percent of the inboard area comprised of a 2732 mm ROC convex section and a 25 percent aspherical outboard surface area. All mirrors were rectangular with dimensions of 152 mm wide by 89 mm high (except for the horizontally split mirror, which had an additional 152 mm wide by 32 mm high convex strip beneath the normal 152 mm wide by 89 mm high surface). Drivers completed lane-change and merge scenarios. Results indicated that drivers made fewer errors (that is, they did not choose to execute unsafe lane changes) when using the 2032 mm ROC spherically convex mirror as opposed to the other configurations tested. Additionally, the 2032 mm spherically convex mirror had an overall high level of acceptance by participants.

Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) performed a series of on-road experiments examining driver performance with different types of mirrors. Wierwille et al. had drivers perform passing maneuvers, maneuvers requiring the driver participant to merging in-between two vehicles, and gap acceptance tasks (using a button press to mark the last safe gap the driver participant would accept) on a closed test track. Driver side rearview mirrors examined included planar, convex (2000 and 1400 mm ROC), aspheric (1400 mm ROC with a 73 percent spherically convex inner portion, and 2000 mm ROC with a 66 percent spherically convex inner portion), and two elongated (one flat and one 1400 mm ROC convex) mirrors. There was a significant effect for the type of mirror on cut-in distances for both the passing and merging maneuvers. Generally, as the ROC of the mirror was increased driver participants allowed for more conservative (safe) cut-in distances. The elongated planar mirror produced the greatest average cut-in distance (approximately 23 m), while the planar and 2000 mm ROC aspheric mirror produced almost identical cut-in distances (approximately 22 m). There were no significant differences between the planar and either 1400 or 2000 mm ROC aspheric mirrors used in the study for cut-in distance. All mirrors produced cut-in distances within 2.35 m of each other. No significant effect of mirror type was found on the last safe gap drivers would accept in the gap acceptance task.

FIELD OF VIEW AND RADIUS OF CURVATURE EFFECTS

In direct vision settings, humans are generally able to make accurate judgments of the distance to an object at approximately 2 to 3 m. The addition of ground information (such as background objects) supports these judgments, while the restriction of the surrounding background tends to lead the observer to underestimation of target distances (Wu, Ooi, & He, 2004). This was noted by Gibson (1950, 1966; cited in Fisher & Galer, 1984), who suggested that the entire optic flow field is used by the observer in the perception of the world. This view combines distances and movements into one, unified, judgment process on behalf of the observer. When viewed through a planar mirror, the optic flow field is presented in an undistorted manner. This allows drivers to take advantage of a direct perception process. However, non-planar mirrors distort (through minification) both the object of interest and the surrounding optic flow field. Thus, the entire process of perceiving a scene is no longer a direct perceptual process and must involve some level of cognitive processing for the driver to reach a decision on an object’s position and motion.

Providing a wider field of view to the driver would help eliminate many of the blind spots surrounding a vehicle. However, achieving this is not a simple matter. The mirror size can be increased (within reason) or the convexity of the mirror can be changed (with the resultant image minification distorting the virtual image). Although additional mirrors can be added, Bockelmann (1991) stated that these mirrors can prove difficult for some drivers to adapt to. Morrow and Salik (1962) noted this, advocating mirrors with an ROC of less than 1041 mm (which the authors identified as commonly used), especially in scenarios of heavy traffic or faster travel speeds.

Jani and Menezes (1962) measured the time required to focus on, and respond to, an image presented in both spherically convex (approximately 1041 mm ROC) and planar mirrors. Snellen letters were presented through two mirrors. The primary (planar) mirror was mounted directly ahead of the participant, while the second was placed to the right (positioned similarly to a rearview mirror). The second mirror was varied between planar and convex mirrors. Targets were presented at a distance of approximately 6 m from the participant. Participants were required to read the Snellen letter presented on each mirror, with letters changing on one mirror while the letter on the other mirror was read. Increasing convexity (decreasing ROC) of mirrors was found to be associated with increases in response time to the acuity task. Results of the study indicated that convex mirrors had a greater response time (1.20 s) as compared to planar mirrors (1.08 s).

One of the larger-scale studies of rearview mirror configuration was conducted by Burger (1974). This study involved on-road testing of 12 different combinations of mirror systems. The mirrors examined included three periscopic systems, six 2-mirror systems (three including a periscopic interior rearview mirror), and three 3-mirror systems (one including a convex side rearview mirror, one including two convex side rearview mirrors, and one Fresnel lens). The test route consisted of an approximately 19 km section of freeway and multilane streets. Measures of glance duration and frequency were obtained from drivers completing 22 total mirror-related traffic maneuvers (including left and right freeway entrances, exits, merge, and lane changes, as well as surface street lane changes). Although drivers were prompted to make the maneuver by an in-vehicle experimenter, they only began executing the maneuver once they believed it was safe to do so. Analysis revealed that the maneuver time was lowest for the systems with the largest FOV (which, in this study, were all periscopic systems). No statistical differences were present between the combinations of convex mirror systems examined and a conventional (planar) mirror system. Likewise, no performance differences were present for drivers between the planar and convex mirror systems used in this study. It is important to note that systematic testing differences preclude drawing firm conclusions from this work; both the vehicle and test mirror system varied, making it impossible to separate effects of vehicle from effects of mirror.

In a laboratory experiment, Mortimer and Jorgeson (1974) examined drivers' ability to detect the presence of a vehicle using three types of mirrors. Participants viewed motion pictures of a roadway scene through mirrors under reduced lighting conditions. In some scenes, a car approached as if to overtake the car in the driver's viewpoint position. Participants provided a forced choice response to three conditions: no car present, a car visible in the participant's own travel lane, and a car visible in the adjacent passing lane. The mirrors used included a planar mirror and two convex mirrors (with ROCs of approximately 914 and 1219 mm). In addition, the cars in the detection task were filmed with their headlights both on and off. There were no significant differences in the number of errors made based on the convexity or type of mirror, nor were there any differences in reaction time based on the convexity or type of mirror used.

Early research examining convex mirrors demonstrated that driving experience interacts with drivers' ability to process the distorted images produced by non-planar mirrors. Walraven and Michon (1969) examined driver performance in lane change/vehicle overtaking maneuvers while drivers used one of three mirrors (planar, 600 mm convex, or 1200 mm convex; each mirror was approximately 150 by 220 mm in size). While performing a car-following task, the rearview mirror was shuttered as a confederate vehicle approached in an adjacent lane from the rear. At a set distance, the shutter was opened and participants responded as to whether or not an acceptable passing gap was present. The findings indicated a significant experience by mirror interaction; more inexperienced drivers' gap acceptance performance was worsened (i.e., gaps accepted became smaller) as mirror ROC decreased. This effect was magnified as the speed differential between the driver and the oncoming vehicle increased. However, no difference was found in reaction time between planar and non-planar mirrors. One conclusion of Walraven and Michon's work was that convex mirrors with a ROC below approximately 1000 mm are not necessarily any more effective in supporting driver indirect vision than convex mirrors with more extreme ROCs. Additionally, mirrors with ROC of no less than 1200 mm were determined to likely have no effect on driver behavior.

Convex mirror surfaces with a large ROC are of interest to researchers. Since prior research suggests that driver overestimation of distances is positively related to the convexity of the mirror, the use of a large ROC convex section in an aspheric mirror may alleviate some of the distance estimation problems. Flannagan, Sivak, Kojima, and Traube (1998) examined the use of five different mirrors in a stationary-driver distance estimation task. The mirrors examined consisted of a planar mirror, and spherically convex mirrors with ROCs of 2100, 3300, 5400, and 8900 mm. All mirrors were of the same dimensions and were mounted on the same test vehicle. Participants performed a distance estimation task, where they estimated the distance to a rearward automobile using an arbitrary scale, with an automobile parked 20 m ahead as a reference standard of 100 units. The type of mirror used was found to have a significant effect on distance estimations. The average distance estimates with the lower ROC mirrors were significantly higher than estimates from less convex mirrors. However, average estimates made with the 8900 mm ROC mirror were still greater than those made with the planar mirror. Additionally, the authors calculated a misestimation index (the ratio of estimates made with the convex mirror to those made with the flat mirror). The misestimation index decreased with increasing ROC. The 8900 mm ROC mirror produced a misestimation of approximately 8 percent greater than estimations from the planar mirror.

There is also concern that viewing distances will have a greater effect on drivers' distance estimation performance with non-planar mirrors than with planar mirrors. This is because increases in eye to mirror (viewing) distances reduce the angle of the image subtended on the retina, which is theorized to interact with the minification produced by non-planar mirror surfaces. This was examined by Flannagan, Sivak, Schumann, Kojima, and Traube (1997). Participants in this stationary-driver study made distance estimations of a rearward vehicle using an arbitrary scale. There was a vehicle parked 20 m in front of the participant to act as a reference value on the scale, and the mirrors used included planar and 1400 mm ROC convex. The results indicated that, while increases in viewing distances did produce greater amounts of overestimation, the effect was not as great as would be predicted by perceptual models of visual angle or vergence/accommodation of the eyes. In comparing the results of the same mirror mounted in either the driver- or passenger-side rearview mirror position, convex mirrors in the further viewing distance passenger-side position produced roughly twice the amount of overestimation of distance as compared to the same mirror in the driver side position.

ASPHERIC CONSIDERATIONS

In addition to issues of perception with convex mirrors, aspheric mirrors have the additional concern of presenting the driver with two distinct image areas: an aspheric mirror can present one image from the main section and a second image from the diminishing radius section (Platzer, 1995). Convex non-planar mirrors do not present this problem as the ROC of the mirror is constant across the curvature. This unique aspheric mirror feature has the potential to result in binocular disparity, which is a situation where there is a difference in the visual angle subtended on each eye. O'Day (1998) examined binocular disparity in four different aspheric mirrors. All mirrors had the same exterior dimensions, and varied in their ratio of spherical to aspheric sections as well as in their ROC within sections (Table 4). Three measures of image disparity (linear, area, and volume) were calculated based on the four mirror types.

Table 4. Mirror Characteristics (from O'Day, 1998)

Mirror System Abbreviation	Percent Inboard Spherical (ROC, in mm)	Percent Outboard Aspheric (ROC Range, in mm)
E1	76.3 (2000)	23.7 (2000 – 58.5)
E2	76.3 (1400)	23.7 (1400 – 60.5)
M1	58.9 (2540)	41.1 (2540 – 171.7)
M2	17.4 (3048)	82.6 (3048 - 376)

The maximum binocular image disparity did not greatly differ from distance to the target (total change was under 9 percent). However, the binocular disparity profiles produced by each mirror differed greatly. The E1 and E2 mirrors that were examined both displayed a very sharp peak (sudden increase in disparity) at the transition point between the convex and aspheric sections of the mirrors. The other two mirrors examined did not display this trend. While O'Day's calculations do not allow for conclusions about driver performance with aspheric mirrors, they do suggest that mirrors with less convexity at transition may result in less image disparity. These findings also highlight the need for further research into target detection issues when an object is presented in or near the transition line of an aspheric mirror. The reader should note that the E1 and E2 systems used in this experiment were modeled on the aspheric designs of Pilhall (1981).

In a psychometric task, De Vos, Van der Horst, and Perel (2001) measured drivers' visual acuity while viewing targets through four different mirror configurations (a planar mirror, a 1400 mm ROC spherically convex mirror, and two aspheric mirrors with ROCs of 1400 and 2000 mm, respectively). Visual acuity through the mirrors was assessed using a Landolt C chart. Results indicated a significant difference in visual acuity through the mirrors (Figure 18). The planar mirror provided the greatest level of effective visual acuity (significantly greater than any non-planar). No significant difference in effective visual acuity was present between any of the non-planar mirrors. Although significant differences in visual acuity may be present, this may be seen as a target identification task instead of a target detection task, with vastly different implications for actual (on-road) driver performance.

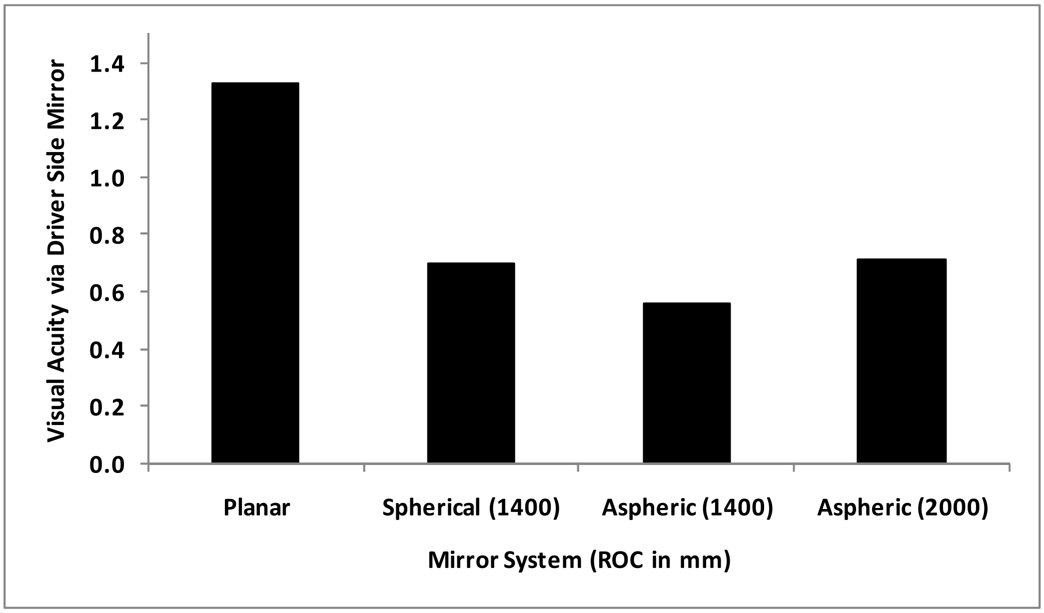

Figure 18. Visual Acuity by Mirror Type (adapted from De Vos et al., 2001)

However, the errors in driver judgment of distance and speed resulting from non-planar rearview mirrors may be offset by the presence of an interior planar rearview mirror. Mortimer (1971) examined this possibility in a study of lane-change maneuvers. Participants in this study performed maneuvers where they passed a slower lead vehicle in the presence of traffic approaching from the rear. Three exterior mirrors were examined: one planar mirror, and two convex mirrors with ROCs of approximately 737 and 1194 mm; a planar interior rearview mirror was also present. Results indicated that distance judgments made using exterior convex mirrors were consistently overestimated, and the associated passing gaps accepted were shorter (and less safe), as compared to the same judgments made using planar mirrors. This overestimation of gap distance was inversely related to the mirror's ROC. There were no differences in driver judgments of speed between convex and planar mirrors. Any potential safety issues in gap acceptance from drivers using non-planar mirrors may lie with judgments of distance and not speed. The author concluded that an ideal convex rearview mirror should have a ROC of greater than 762 mm, which would provide a theoretically optimized tradeoff between FOV and driver performance in gap judgments. Mortimer also noted that, when used in conjunction with an interior rearview planar mirror, differences in gap acceptance based on rearview mirror type collapsed. Thus, the potential detrimental effect of non-planar rearview mirrors may be offset through drivers also acquiring information through the interior rearview mirror. However, this relies upon the assumption that drivers will sample information from both mirrors prior to initiating the lane-change maneuver, something that cannot be guaranteed (Lee, Olsen, & Wierwille, 2004).

Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) examined three driver side rearview mirrors in a stationary-driver experiment. The three mirrors included a planar mirror, a convex mirror with a ROC of 2000 mm, and an aspheric mirror with a 1400 mm ROC, 73 percent, inner spherical section. The outer aspheric section of the 1400 mm ROC aspheric mirror was masked, forcing participants to make judgments based on the inner convex section. This effectively changed the mirror to a 1400 mm ROC convex mirror. Participants performed distance estimations to a target vehicle placed in the adjacent lane at distances of approximately 23, 31, and 44 m rearward. The target vehicle was stationary for the duration of the participant judgment. The results indicated that drivers generally underestimate distances (believe distances present are generally below the true distances). Only the 1400 mm ROC convex section produced an overestimation. No significant differences were present between the various types of mirrors, however (Figure 19).

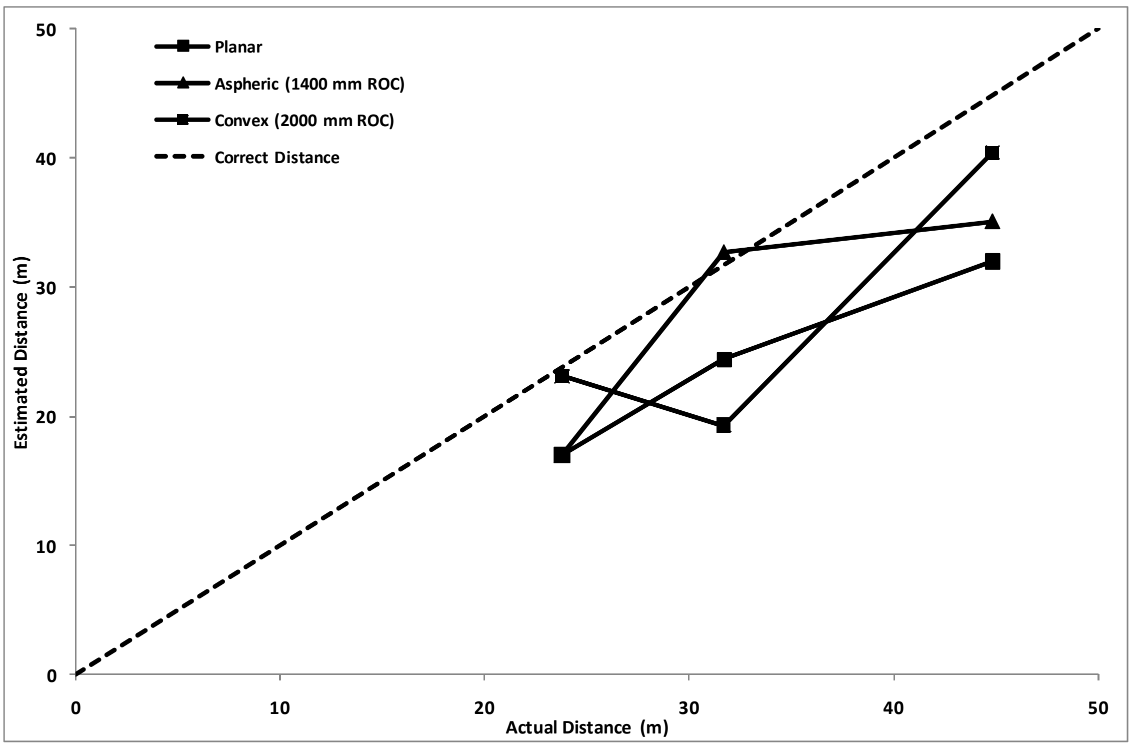

Figure 19. Actual versus Estimated Distances for Three Mirror Types (adapted from Wierwille et al., 2008)

Subjective Responses to Non-Planar Mirrors

Mortimer and Jorgeson (1974) reported a study of drivers' subjective evaluations of planar and convex rearview mirrors in night driving conditions. Six drivers traveled at a fixed speed (80 km/h) on a highway at night while mirror systems were varied. The mirror systems included a planar mirror and two convex mirrors with ROCs of approximately 910 and 1219 mm, respectively. A confederate vehicle followed in a set pattern by approaching at 88 km/h until the gap closed to 15.25 m, slowing to 64 km/h until the gap opened to 91.5 m, and then accelerating until reaching 88 km/h once again. Headlamps on this following car were varied through three settings, and the vehicle remained in the left (adjacent) lane throughout this procedure. During this time, participants were regularly asked to estimate the distance to the following car as a means of forcing mirror glances. Following each trial, participants were asked to provide a rating of the effectiveness of the mirror in reducing glare discomfort and the general visibility provided by the mirror. Although there was a difference in the overall glare rating from the different following vehicle headlamp type, no statistical difference was present in the glare ratings assigned to the three mirror types. Interestingly, the planar mirror was rated the highest as far as providing effective visibility (Table 5).

Table 5. Mirror Glare and Visibility Ratings (from Mortimer & Jorgeson, 1974)

Mirror Type	Glare Rating	Visibility Rating
Planar	2.7	3.7
Convex, 914 mm ROC	2.6	2.7
Convex, 1219 mm ROC	2.5	2.4

Note: Glare and visibility ratings provided on a scale of 1 to 5, with 1 indicating an ineffective system and 5 indicating an effective system.

Kaehn (1975) conducted a 10-month field trial involving 515 drivers using 84 motor pool vehicles that were fitted with two test mirror systems (each system was fitted to 42 vehicles). The systems included:

- Type I: Planar rearview mirror on right side door, convex mirror (1524 mm ROC) on the right fender, larger inside rearview mirror.
- Type II: No door mounted mirror, convex mirror (1270 mm ROC) on each fender, original inside rearview mirror.

Drivers accessed the vehicles through either temporary (dispatch) use, or through long-term assignment to the car and reported their subjective experience with the mirror systems through a questionnaire. A total of 627 questionnaires were received, and the vehicles logged approximately 322,000 km during the test period. Approximately 18 percent of the questionnaires received were from drivers who had used the test cars more than once. Responses to the questionnaire were mixed; while drivers appreciated the greater field of view provided by the convex mirror system, a number of drivers did not trust the mirrors. Additionally, both systems were rated poorly for use in inclement weather. Both systems were rated as better than conventional (planar) mirrors for use in lane-changing maneuvers, freeway driving, and general blind-spot visibility. One of the biggest complaints received was about the non-adjustable nature of the two test systems. This may have been an influencing factor in the drivers' responses to the questionnaire.

In a follow-up to the 1975 study, Kaehn (1976) outfitted 23 vehicles with a system consisting of planar mirrors on the driver-side door and for the interior rearview mirror, and a convex rearview mirror on the passenger-side door of the vehicle. All mirrors were adjustable in this study. As in the earlier study, the vehicles were in a motor pool and drivers either reserved the vehicles for day use or were assigned the vehicles for longer term use. A total of 189 questionnaires (from 147 drivers) were obtained. Results indicated that drivers preferred the mixed system and were comfortable with its use in most situations (including freeway and city use). When the findings were compared against the 1975 questionnaire results, drivers tended to prefer the mixed planar/convex system in the current study as compared to the mirrors of the earlier study. However, this may be a result of the earlier study using non-adjustable mirrors.

Flannagan and Flannagan (1998a) examined five different non-planar mirrors in a study using employees of an automaker. Two convex (1500 and 2000 mm ROC) and three aspheric (34, 40, and 66 percent of the total surface area was aspheric) rearview mirrors were studied, with each participant using one of the five mirrors for a month-long subjective evaluation. The ratings were almost uniformly positive. Overall, 86 percent of participants were comfortable with the non-planar mirrors after only 1 week, while 93 percent were comfortable with the non-planar mirrors after a 4-week period (Table 6).

Table 6. Subjective Response to Test Mirrors (from Flannagan & Flannagan, 1998a)

Mirror Type	Percent Comfortable with Mirror After One Week	Percent Comfortable with Mirror After Four Weeks
Spherical, 1500 mm ROC	90	95
Spherical, 2000 mm ROC	91	100
Aspheric, 34% aspheric area	95	100
Aspheric, 40% aspheric area	87	91
Aspheric, 66% aspheric area	68	82
Overall	86	93

Three things are important to note with these findings. First, participants were drawn from a population with at least some level of interest in automotive technologies. This may have led participants to respond in an overly enthusiastic manner, and caution should be exercised in drawing definite conclusions from the results. Second, participants did not seem to prefer the rearview mirrors with the larger aspheric areas. Finally, participants appeared to keep many of their same mirror behaviors between their normal and the experimental mirrors. While 81 percent of drivers aimed their normal automobile mirrors with the vehicle body visible, 93 percent of these drivers also aimed the experimental mirrors in the same fashion.

De Vos, Theeuwes, and Perel (1999) reported the results of a survey of European drivers with experience using aspheric and convex rearview mirrors. There was a large amount of variability in drivers' knowledge of their vehicle mirror types. Half of the respondents knew what type of mirror system they had, while approximately 25 percent did not know, and the remaining 25 percent answered incorrectly. It was also revealed that drivers currently using non-planar mirrors (either convex or aspheric) that had previous experience driving with a planar mirror preferred using the non-planar variety.

Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) performed on-road testing with a variety of planar, convex (1400 and 2000 mm ROC) and aspheric (with 1400 mm ROC with a 73 percent spherically convex inner portion, and 2000 mm ROC with a 66 percent spherically convex inner portions) rearview mirrors. At the conclusion of testing, drivers were asked to subjectively rate the mirrors they had experienced. The 1400 mm ROC convex and the two aspheric mirrors were rated poorly (in comparison to a planar mirror) in terms of image distortion, uneasiness of use, and comfort level. In addition, Wierwille et al. were able to make comparisons across age and sex categories. The authors concluded that older drivers and female drivers were both less likely to have a favorable subjective response to the presence of non-planar mirrors. Overall, all drivers tended to prefer the planar mirrors. These findings generally agree with the findings of Burger, Mulholland, Smith, and Sharkey (1980) and Burger, Mulholland, Smith, Sharkey, and Bardales (1980), both of which reported that drivers' subjective response to non-planar mirrors worsens as the convexity increases.

Driver Experience and Training

Experience with non-planar rearview mirrors can help improve, but does not necessarily offset the differences in, relative judgments of oncoming traffic. Smith, Bardales, and Burger (1978) studied the relative importance that drivers assign to the areas surrounding a vehicle (especially those areas covered by mirrors), and the effects that convex mirror use training has on driver performance. Using a ranking test on a grid pattern of 20 sections (a 4 high by 5 wide grid was used, with the first row's center square occupied by the rater's "own car;" Figure 20), participants were ask to select the most important zones (in terms of importance for driving safety) surrounding the vehicle.

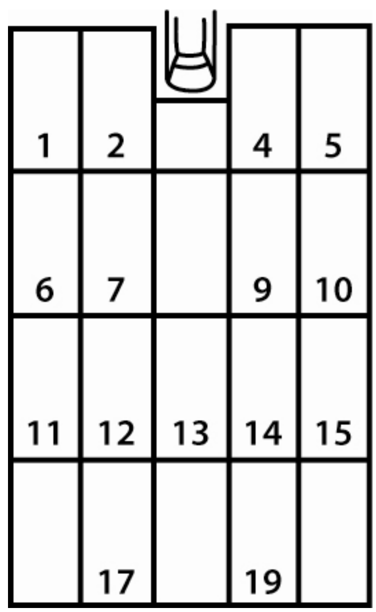

Figure 20. Plot of Zones Surrounding the Vehicle (adapted from Smith et al., 1978)

This was used to determine the criticality of each zone. Overall, zones to the right of the vehicle were selected with slightly greater regularity than zones to the left; however, no statistically significant differences were present (Figure 21). In a follow-up study, Smith et al. (1978) examined the effect of training drivers to use a convex mirror (1270 mm ROC); a control group receiving training on planar mirrors. Following training, the drivers were presented with films showing vehicles approaching at various speeds and distances that had been filmed through either planar or convex mirrors. Drivers viewed these and were asked to make judgments on the stimulus vehicles' speed and distance. Results indicate that training had a large and significant effect on distance estimations. While all drivers were able to greatly improve their absolute accuracy in distance and judgments, drivers in the convex mirror group were able to reach a higher level of performance (greater accuracy) as compared to the group using planar mirrors.

Figure 21. Criticality Assessment by Vehicle Position (adapted from Smith et al., 1978)

Burger, Mulholland, Smith, and Sharkey (1980) reported significant learning effects in the accuracy of participants' distance judgments (regardless of mirror convexity). In general, participants became more accurate in their distance estimations across trials. When examining gap acceptance, the percent of unsafe gaps tended to decrease with increasing ROC. The mirrors with the smallest ROC (508 and 1016 mm) resulted in the largest number of unsafe gaps accepted, while the 2032 mm ROC mirror produced the fewest unsafe gaps accepted. However, no significant difference in the percent of unsafe gaps accepted was found between the 1016, 1397, and 2032 mm ROC mirrors. The subjective analysis revealed that participants consistently rated the mirrors with the greatest convexity as being lowest in terms of confidence and learning time.

Although driver training is often claimed as a way of reducing the number of collisions occurring, Ayres, Gross, and McCarthy (1993) note that the types of collisions which occur are not those that may typically be addressed through driver training. Ayres and co-authors state that while more targeted behavioral approaches are needed, safety equipment that supplements driver safety without requiring action on the driver's behalf is likely to be as effective. Thus, the practical effect of training drivers to use non-planar mirrors may be insignificant.

Flannagan, Sivak, and Traube (1996) examined driver adaptation to different mirror configurations (test mirrors included a planar mirror, a 1000 mm ROC convex mirror, and an aspheric mirror with a 1400 mm ROC inner convex section) in a stationary-driver distance estimation experiment. Participants viewed rearward approaching traffic through one of the test mirrors and provided a distance estimation on an arbitrary scale; the approaching vehicles were between 5 and 40 m behind the driver, and a vehicle was placed in a stationary position 20 m in front of the driver as a reference to the scale (100 units in front of the driver). Performance was measured in three different periods of time, noted as pre-test, training, and post-test periods. Results indicate that driver distance estimation significantly changed over time and training. This effect was not equal across all mirror types. Before training, planar mirrors demonstrated the lowest amount of misestimation. Aspheric mirrors demonstrated a slightly higher amount, while convex mirrors demonstrated the highest amount of misestimation of distance. At post-test, planar mirror performance had only increased slightly, while aspheric and convex mirror estimation performance were approximately equal. However, both non-planar mirrors demonstrated greater overestimations in distance judgments as compared to the planar mirror. The results of this study are interesting, as the training time amounted to approximately 1 hour. This raises questions as to the impact of either additional training and feedback, or design changes, on driver estimations using non-planar mirrors.

Glare

Discomfort and disability glare can be the source of significant problems in driving (Theeuwes, Alferdinck, & Perel, 2002) and is a critical factor in the design of automotive mirrors (Helder, 1987). Discomfort glare is a subjective response to glare and may be experienced as annoying, uncomfortable, or painful; disability glare is a degradation in forward vision from glare sources that results in a loss of contrast sensitivity and the ability to detect objects (Helder, 1991). Helder (1991) developed equations to calculate expected values for both discomfort and disability glare.

Rearview mirrors can complicate this, as glare illumination from headlamps reflected through vehicle mirrors can produce subjectively higher levels of glare as compared to glare from oncoming vehicles (Miller, Baumgardner, & Mortimer, 1974). Drivers have the most difficulty with rearview mirror glare during dusk and dawn, conditions where lighting levels are transitioning from night to day or vice-versa (Mansour, 1971). This problem can be exaggerated by the condition of the following vehicle’s headlamps. Glare from headlamps is greatly affected by the mounting position, beam use (high or low beams), and misalignment of the headlamp (Rowland, Silver, Volinsky, Behrman, Nichols, & Clisham, 1970; Rowland, Moretti, & Patton, 1981). This has raised questions about the glare that is experienced with non-planar rearview mirrors.

Lockhart and Atsumi (2004) examined the effects of headlamp glare on three mirror configurations. Participants were asked to provide a subjective rating of glare (using the De Boer scale, with lower values on the scale indicating worse subjective glare ratings; De Boer & Schreuder, 1967) from light reflected from an automotive high intensity discharge (HID) headlamp in a laboratory setting. The mirrors examined were a planar mirror and two convex mirrors (one was coated with a blue tint). Participants were counterbalanced for age (older: ages 65 to 88 years, and younger: ages 18 to 30 years) and sex. Results indicate that, for the same level of glare as measured by angle of incidence and eye-measured illuminance, older adults reported worse subjective levels of glare as compared to younger adults. Although there was no main effect for mirror type on subjective glare ratings; participants tended to rate subjective glare as worse for the planar mirror as compared to the convex mirrors tested (Table 7).

Table 7. Mirror Reflectance and Subjective Glare Rating by Mirror Type (from Lockhart & Atsumi, 2004)

Mirror	Reflectance (in Percent)	Subjective Glare Rating Mean (SD)
Planar	39.12	5.96 (1.78)
Convex (1400 mm ROC)	8.78	6.18 (1.69)
Blue Tint Convex (1400 mm ROC)	7.77	6.22 (1.73)

Additionally, it should be noted that planar mirrors will normally produce a higher subjective glare rating than convex and aspheric mirrors (Gupta, Wierwille, Spaulding, & Hanowski, 2008). For both discomfort and disability glare, the convexity of a mirror has a direct relation to the size of the glare source; convex mirrors will reduce the size of the glare source. Calculations by Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski (2008) explain the cause of this finding. Higher convexities lead to smaller images with less illumination and typically lower levels of glare as compared to planar mirrors. Experimental evidence for these calculations is available in Flannagan (2005).

Aging Drivers

The older driver typically faces multiple challenges to safe driving from normal age-related visual deficits. These deficits can be brought on by normal deficits associated with aging, but also by the medications and injuries more prevalent in the aging population (Eby, Trombley, Molnar, & Shope, 1998). Ashman, Bishu, Foster, and McCoy (1994) conducted a study of over 100 older drivers (ages 65 and older), specifically examining the possible countermeasures with the potential to improve the safety of older drivers. Although physical therapy and perceptual training/driver education were examined as promising methods of increasing older driver operational safety, none of the countermeasures reached significance. For older drivers to retain the ability to safely operate a vehicle, the authors called for changes in the design of the roadways to improve sightlines. Retaining older driver mobility while maintaining a high level of safety will also require improving the visual information provided to drivers. However, elderly drivers have a predictable degradation of visual acuity over time (Atsumi, 1995), making the acquisition of visual information from driving more difficult.

Older drivers also typically have difficulty perceiving motion, and especially discriminating between multiple concurrent motions (such as a car approaching on a moving background; Ball & Sekuler, 1986). Ball and Sekuler note that training can produce some improvements in motion discrimination in a laboratory setting; however, testing in a road-going population has not been performed. In addition to global deficits in motion perception with aging, there is some evidence to suggest motion perception is particularly affected in older females (Gilmore, Wenk, Naylor, and Stuve, 1992). The older driver also tends to show a global reduction in useful, or functional, FOV (UFOV) as age progresses (Shinar & Schieber, 1991). This effect was noted by Burg

(1968), who reported that the visual field appears to decline at approximately 35 years of age, with the visual field constricting progressively with age. Burg also reported that females do not appear to have the same rate of visual field degradation as compared to males. The UFOV is the total visual field area in which information may be acquired in one visual fixation (Ball & Owsley, 1991). Ball, Beard, Roenker, Miller, and Griggs (1988) note that the age-related reduction in UFOV makes visual searches (such as obtaining information from a rearview mirror) less effective.

Older drivers, along with drivers experiencing injuries or disabilities, can have difficulty in making the gross neck movements needed to view a car mirror. Bulstrode (1987) surveyed 50 drivers with restricted range of motion in the cervical spine in order to determine the suitability of supplementary mirrors. A number of drivers with limited range of motion experienced difficulties in approach roads from the off or adjacent position (72 and 80 percent, respectively). In addition, many drivers in the Bulstrode sample (60 percent) had mounted at least one supplementary mirror on their personal vehicle.

SUMMARY

Studies of visual performance in driving with non-planar mirrors have depended on the use of laboratory, stationary-driver, and on-road testing. Common measures have included eye-glance behavior and errors in distance judgments, as well as driver performance measures such as gap acceptance.

There have been consistent findings in laboratory and stationary-driver testing of human visual performance with non-planar rearview mirrors. Drivers typically overestimate distances when making judgments through non-planar exterior rearview mirrors. Almost all laboratory and stationary-driver testing findings suggest that the likelihood and degree of distance overestimation increases with increasing convexity of a mirror. Findings vary in on-road testing, with differences between study results including the presence or magnitude of this overestimation effect. On-road testing has revealed more complex findings, with results indicating that there is either no difference or reduced gaps accepted when drivers use non-planar mirrors. When there are differences found in on-road testing, the magnitude of differences between planar and non-planar mirrors is consistently less than laboratory and stationary-driver testing results would predict. There is some evidence to suggest that drivers can learn to perform more accurate distance judgments with non-planar mirrors through training and feedback (Burger, Mulholland, Smith, & Sharkey, 1980); however, a systematic investigation of this is warranted. Likewise, drivers may be able to adjust to the diminished (minified) image of a non-planar mirror by relying upon the interior review mirror (Mortimer, 1971). This conclusion was further evidenced by Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008), who found that exterior rearview mirrors have little practical effect on gap acceptance.

Older drivers are another point of concern with the use of non-planar mirrors on vehicles. While some data suggest that older drivers are more likely to benefit from the use of non-planar review mirrors (Mortimer & VanderMey, 1971; Luoma Flannagan, & Sivak, 2000), their acceptance of a new mirror configuration has not been widely tested. Analysis of subjective responses to convex and aspheric mirrors performed by Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) have indicated that older drivers prefer the non-minified image produced by the planar mirrors and would not be likely to have a high level of acceptance for a new mirror type. However, the varied findings in response to driver subjective opinions on non-planar mirrors suggest that further research on driver acceptance (especially older drivers) is warranted.

Some concerns with aspheric mirrors center on the likelihood of glare. Lockhart and Atsumi (2004) did not find any significant differences in subjective glare ratings between planar and convex mirrors. Likewise, Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) reported that aspheric and convex mirrors both produce lower glare ratings as compared to planar mirrors and low convexity non-planar mirrors.

Summaries of the literature findings for human performance issues of detection, identification, and estimations; FOV and ROC effects; and aspheric considerations are provided in Table 8, Table 9, and Table 10, respectively.

Table 8. Summary of Detection, Identification, and Estimation Findings

Reference	Finding
Laboratory and Stationary-Driver Testing	
Sugiura & Kimura (1978)	Non-planar mirrors result in overestimations of distance, speed, and motion. Mirrors between 900 and 1200 mm ROC may represent a trade-off between FOV and driver perception distortion.
Burger, Mulholland, Smith, & Sharkey (1980)	Except for very small ROCs, the convexity of a non-planar mirror does not significantly influence the amount of error in distance estimation. Smaller ROCs lead to overestimations, while larger ROCs lead to underestimations.
Fisher & Galer (1984)	As ROC is decreased, accepted gaps become smaller. This effect is increased by increased speeds.
Helmers, Flannagan, Sivak, Owens, Battle, & Sato (1992)	Reaction times using aspheric mirrors are lower than either convex or planar mirrors.
Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski (2008)	No significant differences are present between planar, convex, and aspheric mirrors in distance estimation tasks. In general, distances perceived through non-planar mirrors are judged to be below the actual distances to the target.
On-Road Testing	
Bowles (1969)	Response time does not change based on mirror type. Drivers using convex mirrors accept smaller gaps.

Burger (1974)	Time to execute a lane change decreases with increased FOV.
Mortimer & Jorgeson (1974)	There were no differences found in average gaps accepted or collision likelihood between convex and planar mirrors. Planar mirrors required more eye glances.
Burger, Mulholland, Smith, Sharkey, & Bardales (1980)	No effect of convexity on gap acceptance. Right lane changes appear to benefit from non-planar mirrors in terms of decreases in eye glances.
Staplin, Lococo, Sim, & Gish (1998)	In a simulator experiment, drivers made fewer lane-change errors (in terms of reduced collision-likely scenarios) when using a 2032 mm convex mirror as compared to planar and aspheric mirrors.
De Vos (2000)	Smaller gaps are accepted with non-planar mirrors. Gap acceptance does not differ between types (convex, aspheric) of non-planar mirrors.
De Vos, Van der Horst, & Perel (2001)	Smaller gaps accepted with non-planar mirrors. Drivers may have difficulty adjusting when driving vehicles equipped with different mirror types.
Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski (2008)	Side mounted rearview mirrors do not play a major role in gap acceptance as drivers primarily rely on the interior rearview mirror. However, mirror type does affect merging and passing during merging maneuvers. As the convexity of the mirror increases, the cut-in distances decrease. There are no significant differences between aspheric and planar mirrors in cut-in distances for merging and passing during merging maneuvers.

Table 9. Summary of Field of View and Radius of Curvature Effects Findings

Reference	Finding
Jani & Menezes (1962)	Increasing convexity leads to increases in reaction time.
Walraven & Michon (1969)	Inexperienced drivers' gap acceptance performance decreases as convexity increases. There are no differences in reaction time between planar and non-planar mirrors.
Mortimer & Jorgeson (1974)	No differences in reaction time or errors based on mirror type or convexity.
Flannagan, Sivak, Schumann, Kojima, & Traube (1997)	Non-planar mirrors do not produce the overestimations that would be predicted based on models of visual angle or eye vergence/accommodation.
Flannagan, Sivak, Kojima, & Traube (1998)	Effects of non-planar mirrors on distance judgments hold for very large (8900 mm) ROC mirrors.

Table 10. Summary of Aspheric Considerations

Reference	Finding
Burger, Mulholland, Smith, & Sharkey (1980)	Performance in distance judgments (regardless of mirror type) improves over time with non-planar mirrors.
Mortimer (1971)	Errors in judgment from non-planar mirrors may be largely offset through drivers' use of the planar interior rearview mirror.
Mortimer & Jorgeson (1974)	No difference in glare ratings between planar and non-planar mirrors.
Kaehn (1975)	Drivers prefer increases in FOV provided by non-planar mirrors, but do not trust the images produced.
Kaehn (1976)	Drivers are comfortable using non-planar mirrors in freeway and city driving.
Smith, Bardales, & Burger (1978)	Training and feedback can improve accuracy of driver judgments of distance and speed through non-planar mirrors.
Platzer (1995)	Aspheric mirrors have the potential to provide different images to the two eyes (binocular disparity).

Flannagan, Sivak, & Traube (1996)	Training improves performance with non-planar mirrors (aspheric and convex) but, even after training, overestimations persist.
Flannagan & Flannagan (1998a)	Drivers quickly adapt to non-planar mirrors. Almost all drivers become comfortable with aspheric mirrors after 4 weeks (except for aspheric mirrors with large variable ROC sections).
O'Day (1998)	Image disparity in aspheric mirrors is worse for mirrors with higher convexity at the transition between convex and aspheric sections.
De Vos, Theeuwes, & Perel (1999)	A survey indicated that only half of European drivers are aware of what type of mirror is present on their vehicle. Drivers with non-planar mirror experience preferred non-planar rearview mirrors.
De Vos, Van der Horst, & Perel (2001)	Visual acuity through non-planar mirrors is lower than in planar mirrors; however, there is no difference between visual acuity between convex and aspheric mirrors. Drivers may have difficulty in adjusting between vehicles with different mirror systems.
Lockhart & Atsumi (2004)	Subjective glare does not differ between mirrors.
Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski (2008)	Glare is lower in convex and aspheric mirrors as compared to planar mirrors. While, overall, drivers preferred planar mirrors, older and female drivers have an even less favorable response to non-planar mirrors.

CHAPTER 5. CONCLUSIONS

MIRROR CONFIGURATIONS

Due to minification effects in non-planar mirrors, larger sizes of mirrors would be required to produce images equivalent to a planar mirror's reproduction of the same image (Seashore & Lundquist, 1968). Although this should be reflected in changes in mirror glance patterns based on mirror size, the results provide a more complicated finding. Larger mirror widths do require smaller head movements on the part of the driver (Bhise, Meldrum, Jack, Troell, Hoffmeister, and Forbes, 1981). However, the wider mirrors do not necessarily change driver eye behaviors (Mourant & Donohue, 1974; Bhise et al., 1981). Mirror shape may also affect driver performance; elongated mirrors can produce a small, but significant, increase in the gaps drivers accept during lane-change maneuvers (Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008).

Burger, Mulholland, Smith, Sharkey, and Bardales (1980) determined that optimal rearview mirror dimensions are between 7.6 and 8.9 cm vertically, and 16.5 to 17.8 cm horizontally. This dimension range was found to have the greatest effect on drivers' ability to quickly and accurately sample information from the rearview mirror. Ideally, the driver side rearview mirror should be placed approximately 18 degrees from the centerline of the driver (Walraven & Michon, 1969).

It is also important to note that many of the increases in FOV provided by larger and non-planar mirrors may be offset by the manner in which drivers adjust their rearview mirrors (Flannagan & Flannagan, 1998a). Because most drivers choose to adjust their rearview mirrors with the side of the vehicle as a reference, the benefits of increased FOV from non-planar mirrors is somewhat offset. Additionally, all conclusions regarding exterior rearview mirror design must be held in the context that drivers also sample information provided by the interior (planar) rearview mirror when executing a lane change (Lee, Olsen, & Wierwille, 2004), and that mirror size does not appear to have a direct relationship with lane-change collisions (Sivak, Devonshire, Flannagan, & Reed, 2008). Any relationship between lane-change collisions and mirror use for light vehicles is more complex than has been revealed in current exterior rearview mirror research.

VISUAL PERFORMANCE

Differences were present in performance outcomes in non-planar mirror tests between laboratory or stationary-driver tests and those tests conducted in an on-road setting. Laboratory and stationary-driver examinations of driver judgment using non-planar mirrors suggested that drivers significantly overestimate distances (drivers believe more of a gap between their own vehicle and an approaching vehicle is present than really exists) and speeds, as well as accept smaller lane-change gaps. Laboratory and stationary-driver testing also finds that drivers have a faster response time to objects presented in non-planar mirrors. On-road testing revealed a more complicated situation, and, when smaller gaps are accepted, the magnitude of difference between planar and non-planar mirrors was not as large as would be predicted from laboratory and stationary-driver testing. Eye-glance behavior is different between the two mirror types. Drivers using non-planar mirrors typically require fewer glances (Burger, Mulholland, Smith, Sharkey, & Bardales, 1980). The exact effect of non-planar mirrors on gap acceptance during lane-change maneuvers is not clear. While some research (Bowles, 1969; De Vos, 2000; De Vos, Van der Horst, & Perel, 2001) indicates that drivers with non-planar rearview mirrors will accept smaller gaps, on-road testing has indicated either no significant differences or only minor differences in gaps accepted (Mortimer, 1971; Mortimer & Jorgeson, 1974; Burger, Mulholland, Smith, Sharkey, & Bardales, 1980; Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008).

The effects that the different convexities of non-planar mirrors have on drivers are fairly consistent across studies. Increasing the convexity of a rearview mirror appears to affect inexperienced drivers more than drivers with more experience (Walraven & Michon, 1969). Interestingly, inflations in distance judgments (overestimations of distance) persist with extremely large ROC convex mirror surfaces (Flannagan, Sivak, Kojima, & Traube, 1998). Surfaces such as an 8900 mm ROC spherically convex mirror, well beyond what some researchers consider “practically flat,” were still producing inflated distance judgments. However, the practical effect of this needs to be assessed through systematic on-road testing before drawing firm conclusions. This is especially critical as drivers appear to reliably sample information from the interior rearview mirror for passing, merging, and lane-change maneuvers (Mortimer, 1971; Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008).

One of the more consistent findings regarding driver performance using non-planar mirrors is that training, exposure, and feedback can all have significant influence on judgment accuracy and gap acceptance performance. Several studies have indicated that, with increased time and exposure to non-planar mirrors, drivers will reduce the amount of error in their distance judgments (in terms of becoming more accurate in their distance judgments) and increase the size of accepted gaps (Smith, Bardales, & Burger, 1978; Burger, Mulholland, Smith, & Sharkey, 1980; Flannagan, Sivak, & Traube, 1996; Flannagan & Flannagan, 1998a).

Due to the fact that multiple distinct visual areas are present on an aspheric rearview mirror (Platzer, 1995), visual distortions such as binocular disparity can occur. This image distortion is more pronounced when there is a higher convexity at the transition point between the spherically convex inner portion and the decreasing ROC outer portion of the mirror (O’Day, 1998). Further testing is needed in this area to determine the performance and subjective opinion effects on drivers. Glare, however, does not appear to be a problem in non-planar mirrors (Mortimer & Jorgeson, 1974; Lockhart & Atsumi, 2004; Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008).

Driver acceptance of, and reaction to, non-planar mirror systems is uncertain. Early research indicated that drivers hold generally favorable reactions to increases in FOV (Kaehn, 1975, who also noted that drivers did not trust the images in the mirrors), and quickly adapt to the introduction of convex and aspheric rearview mirrors (Flannagan & Flannagan, 1998a). It is important to note that these studies were not conducted in general populations of drivers. Those studies which have examined a more general population of drivers have found that drivers prefer the non-distorted images produced by a planar mirror (Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008) or, if an aspheric mirror is used, that the decreasing ROC section not consist of a majority of the mirror (Flannagan & Flannagan, 1998a). However, general surveys of drivers in the European Union have found that only half of drivers are aware of what type of rearview mirror is on their vehicle (De Vos, Theeuwes, & Perel, 1999). Further testing is needed to examine driver preferences for aspheric mirrors with higher ROC inner sections and higher convexity decreasing ROC sections (split mirrors).

ADVANCED MIRROR SYSTEMS

Attempts to supplement, and possibly replace, mirror-based indirect vision systems have been occurring for some time. Camera-based systems have the advantage of providing views to the driver not limited by obstructions from the vehicle's roof support pillars; additionally, images may be combined to form single (panoramic) views which have the possibility to provide more information to the driver in a single eye glance (Hicks, Schofield, Tarnow, & Veiseh, 1999). However, issues regarding the presentation of image information, perception of distance and motion through monitors, the night performance of the system, monitor-produced glare, and reliability, remain to be addressed before such mirror replacement systems can be implemented for the general automotive driving population. In the meantime, lane-change collision avoidance systems have been receiving considerable attention in the research and development community (Hyland, 1995).

Additionally, development of both mixed type and aspheric mirrors has continued. Kesler and Hufstedler (1994) reported on an attempt to provide a distance cue to drivers using a split surface mirror. The mirror consisted of a planar mirror (approximately 2/3 of the total mirror width) with an outer convex section (approximately 1/3 of the total mirror width). A red/orange ring is centered in the convex section of the mirror. This ring provides a standard to judge the distance of objects in the mirror against; objects appearing as large as or larger than the ring indicate that there is an insufficient gap for a lane change (Figure 22).

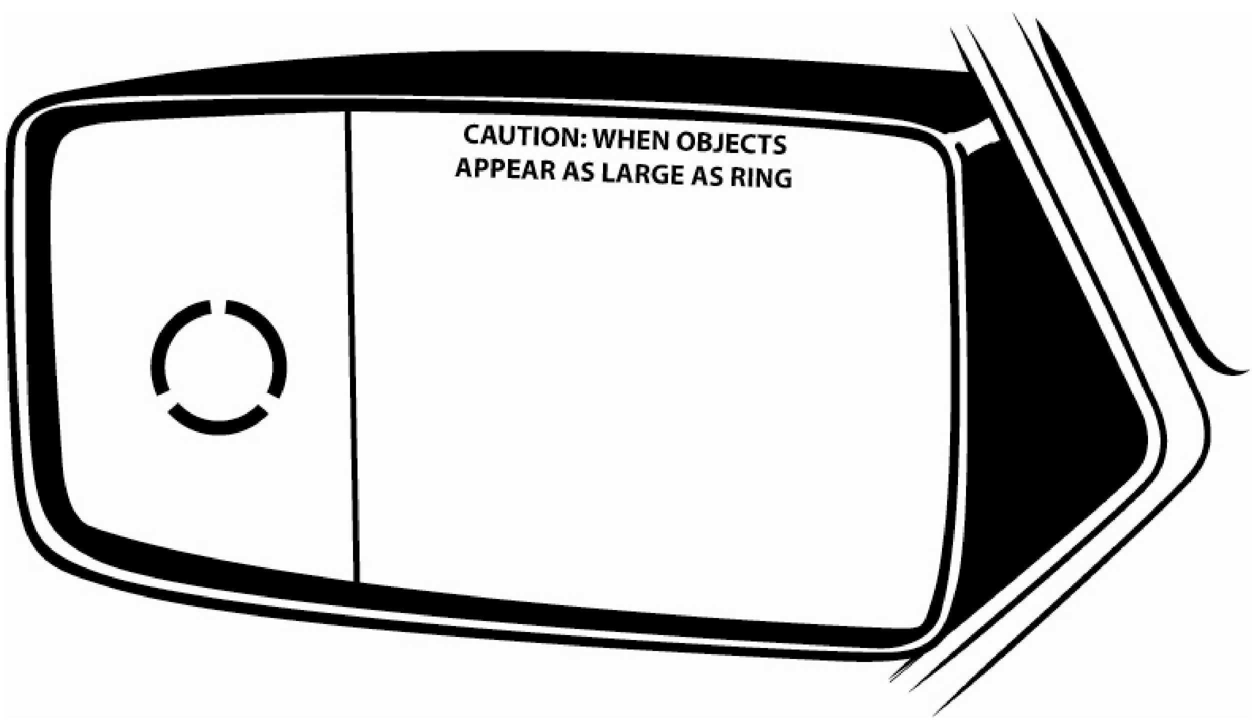

Figure 22. System for Reducing Judgment Errors in Aspheric Mirrors (adapted from Kesler et al., 1994)

Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, and Hanowski (2008) proposed an alternative design which uses a combination of a planar upper mirror (consistent with current U.S. Federal standards) with a lower convex mirror section (however, this occurs at the cost of increased aerodynamic drag and resultant increases in fuel consumption). This allows for both mirrors to be adjusted simultaneously. The upper portion provides the benefits of a planar unit-magnification mirror, such as greater accuracy in distance estimations and gap acceptance performance. The lower convex portion provides a wider FOV for the driver, allowing for the normal blind spots to the side of a vehicle to be seen (Figure 23). The authors note that this configuration would not require the convex portion to have an extreme level of convexity in order to cover the entire lateral blind spot. The presence or absence of certain monocular depth cues (such as converging lines, texture gradient) has an effect on the judgment of size (Meehan & Triggs, 1988). When such depth cues are lacking from a scene, both binocular and monocular judgments tend to overestimate the size of targets. This has direct implications for vehicle indirect vision, as it implies that a sparsity of scene information could possibly interact with the minification effect of non-planar mirrors (a topic that deserves further study). This mirror design is similar to earlier suggestions for an optimized dual-mirror mirror proposed by Burger, Mulholland, Smith, Sharkey, and Bardales (1980) and supports this form of visual processing. Systems resembling these designs are currently in use on light trucks such as the Ford F-150 and Nissan Titan.

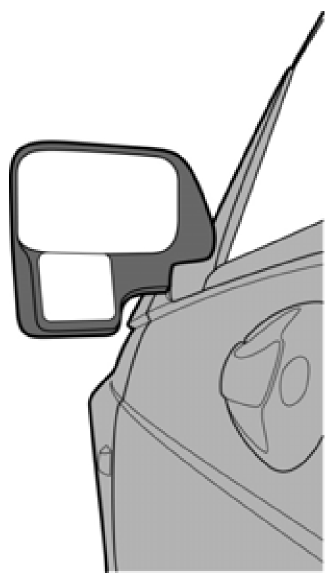

Figure 23. Concept Mirror with Convex Mirror Affixed Below a Planar Mirror (from Wierwille et al., 2008)

FUTURE RESEARCH NEEDS

Besides the need for further efforts at developing practical indirect visibility systems, there is a need to supplement the currently available research on non-planar exterior rearview mirrors with a longitudinal study of driver performance (in terms of gap acceptance and eye-glance behavior), adaptation, and preferences and acceptability when using non-planar mirrors in normal everyday use. Although notable efforts have attempted to gather this type of data through subjective reports, the lack of objective measurements prevents a firm conclusion on the effect of a driver side non-planar rearview mirror. Besides yielding important naturalistic information on U.S. driver lane change and gap acceptance performance with non-planar mirrors, a longitudinal study will help address many of the remaining questions regarding driver adaptation and preferences with non-planar mirrors. These are critical questions, as prior research has indicated that there is some period of time necessary to adapt to a non-planar mirror, and that variables such as mirror convexity have a strong influence on driver acceptance of non-planar mirrors.

Other research has questioned the impact of having situations with mirrors of varying convexity on one vehicle, or having a driver who regularly uses vehicles with multiple mirror configurations (Flannagan, 1988; Flannagan, 2000). These specific situations have yet to be examined. Such a study should also address the question of special populations of drivers, such as the older and the novice driver (Flannagan & Sivak, 1996). Older drivers, as well as people with limited mobility, may have difficulty in using current rearview mirrors. This may result in a different effect (as compared to normal driving populations) in the trade-off between the quality images of a planar mirror and the quantity of information from a non-planar mirror.

Additionally, different configurations of aspheric exterior rearview mirrors should be studied, such as: combinations of planar and aspheric sections in a single mirror frame, strip convex mirrors placed below planar mirrors, and the addition of visual reference marks as to the true size of an object viewed through a non-planar mirror. Prior work has demonstrated that drivers do not prefer an overly large aspheric area (Flannagan & Flannagan, 1998a). However, the rate of change within the variable ROC area has not been studied. The possibility of combining a high rate of change aspheric area with a lower convexity inner portion should be addressed. Likewise, alternative designs (such as proposed in Wierwille, Schaudt, Gupta, Spaulding, Bowman, Wiegand, & Hanowski, 2008) deserve further study, as they provide the undistorted image of a planar mirror combined with the blind-spot information of a convex mirror.

Future research needs in light vehicle non-planar mirror use include the following research questions:

- What effect do convex and aspheric driver side rearview mirrors have on driver performance in normal, everyday, driving?
- How does driver subjective opinions and acceptance of non-planar rearview mirrors change over time?
- Are there advantages to advanced mirror systems that include different mirror types (flat and aspheric, flat and convex) and distance/size reference marks?
- If non-planar mirrors are allowed on the driver side of the vehicle, what is the ideal range of ROC to best support driver performance?

APPENDIX A. BIBLIOGRAPHY AND ABSTRACTS OF SELECTED WORKS

Ashman, R. D., Bishu, R. R., Foster, B. G., & McCoy, P. T. (1994). Countermeasures to improve the driving performance of older drivers. *Educational Gerontology, 20*(6), 567-577.

Presents a study of aged American drivers in the United States to develop and evaluate countermeasures to improve their safety. Use of physical therapy, perceptual therapy, driver education and traffic engineering improvements as countermeasures; Driver performance measurement test; Cost-effectiveness of the countermeasures.

Ayres, T., Li, L., Trachtman, D., & Young, D. (2005). Passenger-side rear-view mirrors: Driver behavior and safety. *International Journal of Industrial Ergonomics, 35*, 157-162.

Passenger-side rear-view mirrors (PRMs) have been standard equipment on motor vehicles sold in the US for many years, although they are not required by the federal motor vehicle safety standards. Numerous studies documented both the apparent need for PRMs (to overcome visual obstructions) and their apparent value (by increasing visual access to the passenger-side rear). In addition, surveys of drivers have found a general appreciation of the importance of sampling visual information from the rear. Very little can be found, however, regarding the actual safety benefit of PRMs. A review of the research literature and several initial studies (driver observation and accident-data analysis), suggest that PRMs may not be associated with any substantial accident prevention, perhaps because they are not consistently used. Implications and research directions will be discussed.

Bhise, V. D. (1973). Visual search by drivers in freeway merging: Implications for vehicle design. *Proceedings of the Human Factors Society, 17*, 152-161.

This paper analyzes the visual field requirements of passenger vehicles in freeway merging situations by studying the match between the visual search and scan behavior of drivers and the angular locations of other merging vehicles moving on side or near collision courses in the visual field of the vehicle. The research was conducted in the following three phases. The first phase results in general indicate that the obstructions created by the left rear roof pillar, in the ramp driver's visual instrumented vehicle. The eye-movement data was analyzed to determine the effects of factors such as driving lane (i.e., ramp lane versus freeway lane), merging road geometry, distance to the merge point, etc., on the visual sampling behavior of the test drivers. The results of the first phase showed that as the merging drivers approach toward the nose of the entrance ramp the visual search and scan behavior of the ramp drivers is dependent upon time-distance from the entrance ramp nose as compared to the drivers merging from the freeway mainstream lane adjacent to the ramp lane. The research in the second phase was, therefore, directed at determining the angular locations of target vehicles (i.e., vehicles approaching from the other merging lane) in the merging drivers' visual field in the vicinity of the entrance ramp nose. A computer simulation program was developed for this purpose. The inputs to the computer program were determined by conducting traffic measurement studies which included collection of data on velocities of different types of vehicles at different locations along the two merging lanes of nine test sites. The third phase involved the analysis of the data obtained from the first two phases to evaluate the criticality of the visual obstructions in the driver's visual field caused by the six roof pillars of the standard four-door sedans. The field, is the most critical of the six obstructions created by the six roof pillars under the right hand freeway merging situations. The results thus suggest that while proposing improvements in the current vehicle designs efforts should be directed towards evaluating alternatives such as minimization of the size of the obstruction created by the left rear pillar, or by devising better rear vision systems with increased field of view, to improve safety at the right hand entrance ramps.

Bhise, V. D., Meldrum, J. F., Jack, D. D., Troell, G. M., Hoffmeister, D. H., & Forbes, L. M. (1981). *Driver head movements in left outside mirror viewing* (Paper No. 810761). Warrendale, PA: SAE.

Two field studies were conducted on public roads to measure driver head movements while using the left outside passenger car mirror. The first study measured the effects of mirror width in the presence or absence of overtaking traffic. Driver head movements during left lane-changing maneuvers were recorded from a lead vehicle equipped with a motion picture camera and a telephoto-zoom lens. Results showed that, in addition to the head turning motions, the drivers made on the average about 2.0 inches of lateral head movements while using one of the four left outside mirror sizes which ranged in width from 2.3 to 10.6 inches. The drivers were also found to make larger lateral head movements when no other vehicles were present in the mirror as compared to when an overtaking vehicle was present. The second study was conducted in no overtaking traffic with one mirror width and used an improved photographic technique. Head movements during left lane changing maneuvers were recorded by a motion picture camera which was mounted in the back of the subject's car and which photographed the image of the driver's head and eyes in the left outside mirror. The data of 25 drivers using a 5.1 inch wide left outside mirror showed that drivers moved their head laterally from 0.4 to 5.0 inches, with a median of 1.5 inches, after turning their heads to search in the mirror. In both field studies, large individual head movement behavioral differences were observed.

Blower, D. (2007). *Truck mirrors, fields of view, and serious truck crashes* (Report No. UMTRI-2007-25). Ann Arbor, MI: University of Michigan Transportation Research Institute.

The driver's direct field of view in a truck is significantly more restricted than that in other vehicles, especially in passenger vehicles. The federal standard that regulates mirror systems on trucks is Federal Motor Vehicle Safety Standard (FMVSS) 111, which requires only a planar mirror on each side of the cab with an area of at least 323 square centimeters. This report analyzes currently available data to examine the traffic safety problems that may be related to truck mirror systems. Analysis of crash data, measurements of fields of view, and observational data on the variety and distribution of mirror configurations in the truck population suggest a need for improved driver vision to address specific truck crash types.

"Mirror-relevant" crash types are defined, identifying crashes in which the truck driver would likely need to use mirrors to maneuver safely. These crash types include lane change/merge (LCM) left, LCM right, left turn with the conflict vehicle approaching from the rear, right turn with the conflict vehicle approaching from the rear, start-up with a pedestrian/non-motorist in front of the vehicle, and backing. Mirror-relevant crashes account for almost 20 percent of all truck crash involvements. LCM right crashes occurred over four times more frequently than LCM left crashes. Similarly, turn-at-intersection crashes in which the conflict comes from the rear are over four times more frequent as right turns than as left. These results illustrate a safety problem in the area where the driver's view is more restricted.

Observational data indicate that about 70 percent of trucks with conventional cabs have right fender mounted mirrors, which can fill in the driver's view along the front right side. Preliminary results from the Large Truck Crash Causation Study (LTCCS), the first to include mirror configuration, suggest that trucks without a right fender mirror may be significantly over-involved in crashes.

Bowles, T. S. (1969). Motorway overtaking with four types of exterior rear view mirror. New York: IEEE.
Eight subjects performed an overtaking task on a three-lane motorway, using each of four arrangements for rear viewing. The rear viewing systems compared were plane or convex mirrors, mounted on either the driver's door or in the conventional wing position for exterior mirrors. On each trial the subject, driving the experimental car, followed a lead vehicle down the inside lane of the motorway. On the approach of a third vehicle from behind, travelling in the second lane, the subject had to decide whether there was time to overtake the lead vehicle. The subject was instructed to perform the maneuver on trials when he judged that the offered gap was large enough. The speed of the following vehicle varied over trials in a random order. The sizes of gaps accepted and rejected were recorded for each mirror-mount combination. Decision times were also recorded. The results suggest that distances are considerably over-estimated with convex, as compared with plane mirrors. The effect is more marked when the convex mirror is mounted on the wing. The implications of these findings for road safety are discussed.

Bulstrode, S. J. (1987). Car mirrors for drivers with restricted neck mobility. *International Disability Studies, 9,* 180-181.
A postal survey of 50 car drivers with restricted movement of the cervical spine revealed that many experienced difficulties when negotiating junctions or reverse parking. In many cases supplementary interior mirrors increased the drivers' field of vision, enabling them to perform maneuvers more safely. Choice of suitable mirrors and their exact positioning depends on the design of the vehicle and the individual's disability.

Burger, W. J. (1974). Evaluation of innovative passenger car and truck rear vision system (Paper No. 740965). Warrendale, PA: SAE.
Twelve passenger and three truck rear vision systems were evaluated under real-world driving conditions using driver looking behavior as performance measures. Glance duration and frequency at each rear vision device, as well as glances made directly to the side/rear scene, by six experienced drivers during 22 traffic maneuvers were recorded using direct video recording of eye movements. Over 20,000 rear information gathering glances were analyzed with regard to glance location, frequency, duration, total glance time per maneuver, and number of glances per maneuver for each system. Superior rear vision systems were identified and design implications regarding multiple device systems, convex devices and field of view were drawn. Ground plot field of view maps and Docket 71-3a target field of view coverage for each system was determined. A secondary study used expert judgment techniques to

obtain estimates of rear scene zone criticality. Criticality weights of zones to the side and rear of passenger vehicles were derived.

Burger, W. J., Mulholland, M. U., Smith, R. L., & Sharkey, T. J. (1980). ***Passenger vehicle, light truck and van convex mirror optimization and evaluation studies: Volume 1, Convex mirror optimization*** **(No. DOT HS 805 695). Washington, DC: U.S. Department of Transportation.**

A series of studies were designed and conducted to evaluate passenger car and truck mirror configurations and convex mirror radii of curvature and to identify the most effective mirror systems for actual on-the-road use. The studies were conducted in two phases, during which over 40 combinations of mirror convexities and mirror configurations were evaluated experimentally. Phase 1, which is reported in Volume 1, was directed toward investigating the effect of mirror convexity on driver judgments of adjacent lane following vehicle speed, distance and accepted lane change gap size. The convexity(s) resulting in the best performance were to be used in subsequent on-the-road performance tests. Mirrors of 20, 40, 55 and 80 inch radii of curvature were fabricated in several configurations specifically for a passenger car, light pickup truck and a van. Configurations ranged from viewing the proposed FMVSS 111 passenger vehicle (PV) targets with plane mirrors and convex mirrors of varying radii to mirror systems viewing the truck (TRK) targets with a single mirror of varying convexity or a combination of plane and convex mirrors viewing those targets separately. Male and female drivers under 30 and over 50 years of age provided over 12,000 speed and distance judgments. Results indicated that performance differences between mirror convexities were small and generally not significant because of extensive practice. Since the 80 inch radii mirrors produced large obscurations in the forward field of view (FOV) and since some of the 20 inch radii mirrors yielded significantly poorer performance and all such mirrors were rated low by drivers, convexities selected for further study were those of a 40 and 55 inch radii.

Burger, W. J., Mulholland, M. U., Smith, R. L., Sharkey, T. J., & Bardales, M. C. (1980). Passenger vehicle, light truck and van convex mirror optimization and evaluation studies: Volume 2, Evaluation of alternative mirror configurations (No. DOT HS-805-778). Washington, DC: U.S. Department of Transportation.

Volume 2 reports on the second phase of a study directed toward investigating performance of different mirror configurations, comprised of 40 or 55 inch convexities, during actual on-the-road lane changing. Passenger car, truck and van original equipment mirrors were compared to 55 inch single mirrors viewing the SR passenger vehicle target and single 40 inch convex and plane/convex mirror combination mirrors viewing the truck X and Y targets. Systems were tested with and without the inside mirror FOV available. Drivers' eye movements were recorded during on-the-road driving involving 22 left and right freeway and city lane changes. Various performance measures were recorded, the primary one being the amount of looking time required to make a safe lane change with a particular mirror system. That measure was based upon looking frequency and time to gather rear information. Results indicated the need to modify FMVSS 111 proposed FOV targets, notably increasing the width of XR, overlapping of X and Y targets. A final series of tests was conducted to answer specific questions about passenger car right mirror location and convex mirror night performance and to evaluate further refinements of passenger car systems. Results indicated that drivers

preferred mirrors with substantially greater vertical height and FOV than proposed FMVSS 111 targets will require, and that this preference was supported by on-the-road performance measures.

De Vos, A. P. (2000). Non-planar driver's side rearview mirrors: A survey of mirror types and European driver experience and a driver behavior study on the influence of experience and driver age on gap acceptance and vehicle detection (No. DOT HS 809 149). Washington, DC: U.S. Department of Transportation National Highway Traffic Safety Administration.
Some European drivers have been using different types of convex, driver-side rear-view mirrors which provide a wider field-of-view than flat mirrors, but produce a minified image. With a minified image, some drivers may have difficulty judging distances and approach speeds. To assess the potential benefits and difficulties experienced by European drivers using non-planar driver-side rearview mirrors, this research included a survey of mirror use as well as an experiment to measure the performance of drivers when making lane change decisions based on mirror information. In addition, an inventory of mirror characteristics on vehicles in use was performed. The survey found that only one third of the drivers knew what optical type of mirror they had. The field experiment quantified the tradeoff between drivers' improved detection of adjacent vehicles due to wider fields of view and their decision to make lane changes at smaller gaps to approaching vehicles. Drivers' experience with non-planar mirrors did not generally compensate for the negative effect of accepting smaller gaps, with the exception of drivers who were accustomed to spherical convex mirrors. There was no increase in the visual workload required to process information in non-planar mirrors. The conclusion was that the relative benefits of non-planar mirrors should be greater than the negative effects.

De Vos, A. P., Theeuwes, J., & Perel, M. (1999). Nonplanar rearview mirrors: A survey of mirror types and European driver experience (Paper No. 1999-01-0658). Detroit: SAE.
A study is being conducted to investigate the effects of driver's side rearview mirror types (either flat or nonplanar mirrors) on driver behavior. The study consists of a survey of mirror characteristics, interviews and questionnaires as a field experiment. The present paper gives the results of the first phase of exploratory interviews. A structured list of questions was used to gather extensive information on mirror use habits, on problems drivers have experienced, on their awareness of mirror characteristics and on background variables. The 47 respondents were categorized by age group (younger / older drivers) and driver's side mirror type (flat, convex, aspherical). The results of this exploratory phase serve as a basis for a revised questionnaire to be used for a large sample of drivers.

De Vos, A. P., Van der Horst, R., & Perel, M. (2001). ***Non-planar rearview mirrors: The influence of experience and driver age on gap acceptance and vehicle detection*** **(No. 2001-01-0321). Washington, DC: National Highway Traffic Safety Administration.**
Some European drivers have been using different types of convex, driver-side rearview mirrors which provide a wider field-of-view than flat mirrors, but produce a minified image. With a minified image, some drivers may have difficulty judging distances and approach

speeds. To assess the potential benefits and difficulties experienced by European drivers using non-planar driver-side rearview mirrors, this research included a survey of mirror use as well as an experiment to measure the performance of drivers when making change decisions based on mirror information. In addition, an inventory of mirror characteristics on vehicles in use was performed. The survey found that only one third of the drivers knew what optical type of mirror they had. The field experiment quantified the trade-off between drivers' improved detection of adjacent vehicles due to wider fields of view and their decision to make lane changes at smaller gaps to approaching vehicles. Drivers' experience with non-planar mirrors did not generally compensate for the negative effect of accepting smaller gaps, with the exception of drivers who were accustomed to spherical convex mirrors. There was no increase in the visual workload required to process information in non-planar mirrors. The conclusion was that the relative benefits of non-planar mirrors should be greater than the negative effects.

Fisher, J. A., & Galer, I. A. R. (1984). The effects of decreasing the radius of curvature of convex external rear view mirrors upon drivers' judgments of vehicles approaching in the rearward visual field. *Ergonomics, 27*(12), 1209-1224.

Two experimental techniques are explored for laboratory investigation of the effect of reducing the radius of curvature of externally mounted rear-view mirrors, using filmed stimulus material prepared to maintain the ecological validity of the changing information display at the mirror surface. One method is concerned with the effect upon the 'minimum safety margin' which drivers are prepared to leave in committing themselves to an offside lane change maneuvers in front of a vehicle approaching from the rear. The second method is concerned with providing a continuous record of differences in the change over time in visual sensation caused by viewing the approach of a target vehicle through mirrors of different radii. The importance of distorted time-to-collision processing on the part of the observer is stressed.

Flannagan, C. A. C., & Flannagan, M. J. (1998). *Acceptance of nonplanar rearview mirrors by U.S. drivers* (Paper No. 980919). Detroit: SAE.

Five different nonplanar mirrors were evaluated as driver-side rearview mirrors in a field test using Ford employees. Two were spherical convex (differing in radius of curvature), and three were aspheric (differing primarily in the proportion of their surfaces over which radius of curvature was variable). Each participant drove for four weeks with one of the nonplanar mirrors. At three times during the test the participants filled out questionnaires concerning their experience with the mirrors. Driver preferences for the experimental mirrors increased moderately between surveys at one week and at four weeks. At four weeks, all five nonplanar mirrors were preferred to the standard flat mirror by at least a small amount. For each of the five mirror designs there was a large range of opinion. Most notably, a small number of people strongly disliked the aspheric design that involved the largest variable-radius area. These results indicate that nonplanar mirrors are likely to be welcomed by a large number of U.S. drivers, but some designs seem more acceptable than others, and for almost any design there may be a small but significant number of drivers who strongly prefer planar mirrors. The sample in this study had a limited range of subject ages, a relatively small number of females, and may have been biased toward people who have generally positive attitudes toward new technologies. The results should therefore be considered preliminary.

Flannagan, C. A. C., & Flannagan, M. J. (1998). *Predicting mirror adjustment range for driver accommodation* (Report No. UMTRI-98-45). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Although the question of how large a driver's outside rearview mirror must be in order to see a specified target has been addressed in other publications, the related problem of required adjustment range has not. In this paper, we present a series of equations that predict, for a given vehicle, the size and location of the mirror adjustment range needed in order to accommodate some percentage of the driver population (e.g., 96%). To complete the calculations for 96% accommodations, eye locations in the vehicle are represented by the 99% SAE J941 eyellipse. Because the transformation from eye location to target location in the mirror will not preserve the tangent properties of the eyellipse, we propose a method in which the side and plan views of the eyellipse are treated separately. Eye location in plan view affects only horizontal adjustment of the mirror, and eye location in side view affects only vertical adjustment of the mirror. In each view, there are two points that lie on lines that are tangent to the eyellipse and pass through the mirror center. These two points are used to represent two extremes of mirror adjustment. Thus, we exclude the 2% of driver eye locations that lie outside either of the tangent lines (no cases lie outside both, so each tangent excludes 1%). In plan view, eye locations must first be adjusted for head turn. We also present equations to calculate mirror adjustment, referenced to an arbitrary line, for each of the four tangent points, given a specified target. We discuss various choices of target location and type, including centered point targets, centered extended targets, and targets that are located at the edge of the field of view. For the latter target type, the calculation of head turn is somewhat different than for centered targets, but the rest of the calculations are the same. The end result of these equations is a rectangle in two-dimensional mirror-adjustment space such that 96% of drivers can find a suitable mirror position within those bounds. An example is carried out using dimensions from a specific vehicle and a target located at the inner edge of the field of view, in order to illustrate the procedure.

Flannagan, M. J. (1988). *Human performance aspects of rearview mirrors: An applied-literature review* (Report No. UMTRI-88-20): University of Michigan Transportation Institute.

This document reviews the literature in the collection of the University of Michigan Transportation Research Institute that is relevant to either of two human performance aspects of rearview mirrors: 1) the tradeoff between visibility and glare due to rearview mirrors, and 2) possible negative perceptual consequences of the use of convex mirrors. Information from relevant items is summarized, and, when possible, presented in tabular form. Original abstracts are presented for the items that include them. A number of areas in which existing work could be extended are identified and discussed.

Flannagan, M. J. (2000). Current status and future prospects for nonplanar rearview mirrors (Paper No. 2000-01-0324). Detroit, MI: SAE.

The Federal Motor Vehicle Safety Standards currently require driver-side rearview mirrors to be flat. For rearview mirrors of typical size, this requirement normally results in a blind zone on the driver side that is large enough to conceal an average size passenger car. In recent years a number of studies have suggested that nonplanar rearview mirrors may be an effective solution to this problem. This paper reviews the evidence on possible effectiveness of nonplanar mirrors, assesses the strength of that evidence, and makes tentative recommendations. The main conclusion is that the use of nonplanar mirrors would probably result in a net gain in safety, but that the effectiveness of the mirrors is likely to depend on details of how they are implemented. Issues that should be resolved by additional research (some of which is already underway) are: (1) How would U.S. drivers respond to a mixed fleet of vehicles, some of which had flat mirrors and some of which had nonplanar mirrors? (2) If nonplanar mirrors are allowed, what range of designs (from among spherical convex mirrors of various radius of curvature, and different versions of aspheric mirrors) should be used?

Flannagan, M. J. (2005). ***Rearview mirror glare with varying vehicle geometries*** **(Report No. UMTRI-2005-25). Ann Arbor, MI: The University of Michigan Transportation Research Institute.**

The potential glare from rearview mirrors was quantified in simulated encounters using data on the locations of mirrors and headlamps, and on the photometric output of low-beam headlamps. This was done for two classes of vehicles (passenger cars, and light trucks and vans [LTVs]) in the roles of the vehicle subject of the glare and the vehicle producing the glare.

The results indicate that, in many encounters with glare vehicles to the rear, there will be a substantial disparity in glare, both among vehicles of different classes and among different mirror locations on a single vehicle. The main reason for this is the strong role of mirror height in determining how much a mirror is exposed to the lower and therefore stronger, portion of a low-beam light pattern. There is substantially greater potential for high glare values on the mirrors of passenger cars versus LTVs, and on the driver-side mirror versus the center rearview mirror on all vehicles. With upward misaim of headlamps, these disparities are increased, as is the absolute level of potential glare. The relatively low potential for glare on the center mirrors of LTVs will often be compounded by the low transmittance of privacy glass on those vehicles.

The present results have implications for where glare light should be sensed in order to control automatic anti-glare mirrors. However, specific recommendations should incorporate two additional considerations: (1) the geometry of a given vehicle, including the actual heights of the rearview mirrors and how the potential fields of view of those mirrors are affected by opaque parts of the vehicle, and (2) quantification of the exposure to glare that vehicles experience in actual traffic, including the frequencies at which glare vehicles are encountered in the fields of view of the individual mirrors.

Flannagan, M. J., & Sivak, M. (1989). ***Nighttime effectiveness of rearview mirrors: Driver attitudes and behavior*** **(Report No. UMTRI-89-32). Ann Arbor, MI: The University of Michigan Transportation Research Institute.**

The availability of new technology for antiglare rearview mirrors has increased the importance of understanding how people react to glare from rearview mirrors, and what the tradeoffs between visibility and glare reduction should be. We conducted a survey of attitudes toward and use of prism mirrors to determine what guidance that information might offer for future mirror design. The major findings are that (1) there is a high level of awareness and use of prism mirrors, but (2) the benefits obtainable from the antiglare setting of the prism mirror are not fully utilized. The reasons for this suboptimal use appear to be (1) a lower than

desirable level of reflectivity on the antiglare setting, and (2) failure to make the required manual adjustments of the mirror setting.

Flannagan, M. J., & Sivak, M. (1996). ***Workshop on rearview mirrors human factors research needs: Summary of recommendations*** **(Report No. UMTRI-96-27). Ann Arbor, MI: University of Michigan Transportation Research Institute.**
This document provides a summary of suggestions for research concerning rearview mirrors that were made at a workshop held at the University of Michigan on May 8 and 9, 1996. The workshop was sponsored by the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation, and conducted by the University of Michigan Transportation Research Institute (UMTRl).

The purpose of the workshop was to identify future human factors research needed for determining rearview mirror performance and design requirements that will insure that drivers can use rearview mirrors safely and effectively. Although the workshop was sponsored by NHTSA, it was intended to identify the most important research needs in the area of rearview mirrors quite broadly, whether or not it was related to NHTSA regulatory activities and independent of who might sponsor the research.

Forty-five individuals participated in the workshop, including representatives of the research community, the regulatory area, and the mirror and vehicle manufacturing sectors.

Flannagan, M. J., & Sivak, M. (2003). ***Framing effects on distance perception in rear-vision displays*****: SAE.**
The increasing availability of camera-based displays for indirect vision in vehicles is providing new opportunities to supplement drivers' direct views of the roadway and surrounding traffic, and is also raising new issues about how drivers perceive the positions and movements of surrounding vehicles. We recently reported evidence that drivers' perception of the distance to rearward vehicles seen in camera-based displays is affected not only by the visual angles subtended by the images of those vehicles, but also by the sizes of those images relative to the sizes of the displays within which they are seen (an influence that we have referred to as a framing effect). There was also evidence for a similar, but weaker, effect with rearview mirrors. In this paper, we further investigate the possibility of framing effects in rearview mirrors by comparing distance judgments made in a typical center rearview mirror (with a larger frame size) to judgments made in a typical driver-side rearview mirror (with a smaller frame size). Distance judgments were the same in the two mirrors; there was no evidence for a framing effect. Current results do not provide a definitive explanation for the apparent difference in framing effects between rearview mirrors and camera-based displays. Among the issues that should be addressed by future work are the possibility that frame effects are generally weaker with large displays and the possible role of learning in how people perceive distance in camera-based displays.

Flannagan, M. J., Sivak, M., Kojima, S., & Traube, E. C. (1998). ***A field study of distance perception with large-radius convex rearview mirrors*** **(Paper No. 980916). Warrendale, PA: SAE.**
One of the primary reasons that FMVSS 111 currently requires flat rearview mirrors as original equipment on the driver's side of passenger cars is a concern that convex mirrors might reduce

safety by causing drivers to overestimate the distances to following vehicles. Several previous studies of the effects of convex rearview mirrors have indicated that they do cause overestimations of distance, but of much lower magnitude than would be expected based on the mirrors' levels of image minification and the resulting visual angles experienced by drivers. Previous studies have investigated mirrors with radiuses of curvature up to 2000 mm. The present empirical study was designed to investigate the effects of mirrors with larger radiuses (up to 8900 mm). Such results are of interest because of the possible use of large radiuses in some aspheric mirror designs, and because of the information they provide about the basic mechanisms by which convex mirrors affect distance perception.

Subjects' distance perceptions for objects seen in large-radius rearview mirrors were measured by magnitude estimation in a static field setting. The results indicate that overestimation of distance continues to decrease as mirror radius increases beyond 2000 mm, and that the overestimation continues to be substantially lower than would be predicted from a model based on image minification and reduction of visual angle. However, even at the longest radius examined in this experiment (8900 mm) the overestimation of distance (8%) is not small enough to be dismissed definitively as trivial. Because various learning effects and changes in driver strategy may compensate for the distortion of distance perception, this does not necessarily mean that convex mirrors of any radius are unsafe. But it suggests that, even for convex mirrors with very long radiuses, the gain in quantity of field of view provided by the convexity comes with a nontrivial cost in quality of field of view, and that the tradeoff between these two characteristics must still be considered in designing optimal mirrors.

Flannagan, M. J., Sivak, M., Schumann, J., Kojima, S., & Traube, E. C. (1997). *Distance perception in driver-side and passenger-side convex rearview mirrors: Objects in mirror are more complicated than they appear* (Report No. UMTRI-97-32). Ann Arbor, MI: University of Michigan Transportation Institute.

Convex rearview mirrors are currently prohibited in the U.S. as original equipment on passenger cars except for the exterior, passenger-side position. One of the primary reasons for this restriction is a concern that convex mirrors may cause drivers to overestimate the distances to following vehicles and therefore make unsafe maneuvers. There is a considerable amount of empirical evidence that convex mirrors do cause overestimation, but the effect is not theoretically well understood. No currently available model successfully predicts the magnitude of the distance overestimation. However, plausible theoretical considerations can be used to generate a previously untested prediction that, even if only qualitatively accurate, would be of practical significance: Eye-to-mirror distance should have a substantial effect on the magnitude of overestimation caused by convex mirrors. Specifically, longer eye-to-mirror distances (as are typical for passenger-side mirrors) should lead to more overestimation than shorter distances (as are typical for driver-side mirrors).

This prediction was tested in a field experiment in which flat and convex mirrors were used on a car in both the driver-side and passenger-side exterior rearview mirror positions. Longer eye-to-mirror distance did lead to greater overestimation, although--as in previous studies--in both mirror positions the degree of overestimation was less than predicted by quantitative modeling. These results suggest that, to the extent that overestimation of distances to following vehicles is a concern for the use of convex rearview mirrors, that concern is less strong for the driver-side exterior position (which is relatively near to the driver's eyes) than for passenger-side exterior position (which is relatively far from the driver's eyes).

Flannagan, M. J., Sivak, M., & Simpson, J. K. (2001). ***The role of binocular information for distance perception in rear-vision systems*** **(Report No. UMTRI-97-32). Detroit, MI: SAE.**

New developments in the use of two-dimensional displays to supplement driver vision have made it more important to understand the roles that various distance cues play in driver perception of distance in more conventional ways of viewing the road, including direct vision and viewing through rearview minors. The current study was designed to investigate the role of binocular distance cues for perception of distance in rearview mirrors. In a field experiment, we obtained data to estimate the importance of binocular cues for distance judgments under conditions representative of real-world traffic. The results indicate that, although binocular cues are potentially available to drivers, these cues probably play little or no role in distance judgments in rearview mirrors in normal driving situations. The present results therefore suggest that the lack of stereoscopic depth cues in two-dimensional displays used as alternatives to rearview mirrors is not likely to have negative effects on drivers' judgments of distance.

Flannagan, M. J., Sivak, M., & Traube, E. C. (1996). ***Driver perceptual adaptation to nonplanar rearview mirrors*** **(Report No. UMTRI-96-4). Ann Arbor, MI: University of Michigan Transportation Research Institute.**

This study examined perceptual adaptation to nonplanar (spherical convex and aspheric) rearview mirrors. Subjects made magnitude estimates of the distance to a car seen in a rearview mirror. Three different mirrors were used: plane, aspheric (with a large spherical section having a radius of 1400 mm), and simple convex (with a radius of 1000 mm). Previous research relevant to perceptual adaptation to nonplanar mirrors was reviewed. It was argued that, in spite of some cases of explicit interest in the process of learning to use nonplanar mirrors, previous research has not adequately addressed the possibility of perceptual adaptation. The present experiment involved three phases: (1) a pretest phase in which subjects made distance judgments but received no feedback, (2) a training phase in which they made judgments and did receive feedback, and (3) a posttest phase with the same procedure as the pretest phase. Initially subjects showed substantial overestimation of distance with the convex mirror relative to the aspheric mirror, and with the aspheric mirror relative to the plane mirror. At the beginning of the training phase, overestimation with the convex mirror quickly diminished, but after about one hour of experience the convex and aspheric mirrors still showed significant overestimation relative to the plane mirror. The present results demonstrate the existence of a rapid, but incomplete, form of adaptation. Whether there is a further mechanism that might operate over a longer time, but lead to more complete adaptation, is an open question that should be addressed by further research. Future research should also address the question of what forms of experience or training are most conducive to adaptation. If substantial adaptation is indeed possible, the use of nonplanar rearview mirrors would be strongly encouraged.

Flannagan, M. J., Sivak, M., & Traube, E. C. (1997). ***Effects of large-radius convex rearview mirrors on driver perception*** **(Paper No. 970910). Warrendale, PA: SAE.**

The U.S. currently requires that rearview mirrors installed as original equipment in the center and driver-side positions be flat. There has recently been interest in using nonplanar mirrors in those positions, including possibly mirrors with large radii (over 2 m). This has provided additional motivation to understand the effects of mirror curvature on drivers' perceptions of distance and speed. This paper addresses this issue by (1) reviewing the concepts from perceptual theory that are most relevant to predicting and understanding how drivers judge distance in nonplanar rearview mirrors, and (2) reviewing the past empirical studies that have manipulated mirror curvature and measured some aspect of distance perception.

The effects of mirror curvature on cues for distance perception do not lead to simple predictions. The most obvious model is one based on visual angle, according to which convex mirrors should generally lead to overestimation of distances. But convex mirrors affect other perceptual cues (including vergence and accommodation) in ways that lead to predictions of underestimation.

Empirical investigations of the effects of mirror curvature have produced a strong consensus that convex mirrors cause overestimation of distance, but several factors can moderate or compensate for that effect. All quantitative studies of the effects of the radius of convex mirrors have demonstrated less overestimation of distance than predicted by the visual-angle model. Shorter-radius (more strongly curved) mirrors generally lead to greater overestimation of distance. Previous studies have examined the effects of mirror radius up to 2 m. There is strong evidence that 2-m mirrors still cause substantial overestimation, and little indication that reductions in overestimation have asymptoted at that radius.

New empirical efforts to study the effects of larger-radius mirrors, beyond 2 m, could both contribute to basic understanding of how mirror curvature affects distance perception, and provide practical information about the possible benefits of using large-radius rearview mirrors.

Flannagan, M. J., Sivak, M., & Traube, E. C. (1999). *Quantifying the direct field of view when using driver-side rearview mirrors* (Paper No. 1999-01-0656). Detroit: SAE.
In a static field study, we tested drivers' abilities to detect vehicles in the periphery of their direct fields of view while they gazed toward the driver-side exterior rearview mirror of a passenger car. The results indicate that both younger and older drivers can detect vehicles with reasonable efficiency even in far peripheral vision. However, the results also indicate that using peripheral vision entails a cost in terms of lengthened reaction time. Although that cost seems modest in comparison with the normal durations of glances to rearview mirrors and of direct looks to the rear, it is not clear from this study alone how the reaction time cost might influence the scanning strategies that drivers actually use in driving. The present study was oriented more to testing drivers' basic visual capabilities than to outlining their overall strategies. Tentatively, it appears that the traditional way of defining the blind zone by assuming a 180 degrees direct field of view is reasonably accurate. The forward limit of the blind zone would therefore be approximately 135 degrees from the straight ahead when a driver looks toward a driver-side rearview mirror that is itself 45 degrees from the straight ahead. Proposed solutions to the blind- zone problem, such as nonplanar mirrors with relatively wide fields of view, should therefore address the zone between the edge of a vehicle and a line about 45 degrees out from that edge.

Gupta, S. K., Wierwille, W. W., Spaulding, J. M., & Hanowski, R. J. (2008). Rated discomfort glare from high-beam headlamp reflection in rear-view mirrors. (Paper No. 08-1771). Transportation Research Board: Washington, DC.

This study compared the rated discomfort glare from vehicle headlamps for different candidate rear-view mirror types in a situation very much like that encountered while driving. The tests were performed using an actual automobile with ten different rear-view mirrors, including the interior center mirror. The test was conducted on a private road, out of traffic, in nighttime conditions. In this experiment the confederate vehicle (large pick-up truck), with its headlamps set on high beam, moved to different positions behind the static subject vehicle. All subjects rated the glare at each position using the glare scale. The results provide a direct within-subject comparison of the various types of mirrors and are consistent with previous analyses. Flat mirrors proved to produce the highest ratings of reflected glare. The aspheric and convex mirrors having a 1400 mm radius of curvature produced lower glare ratings than other outside rear-view mirrors tested. However the glare ratings of 1400 mm radius of curvature mirrors averaged about one rating value higher in glare than the inside rear-view mirror in the nighttime setting. Compared to an interior mirror that is adjusted to manual nighttime setting the outside mirrors produced higher glare ratings. The findings of this research also indicate, surprisingly, that older drivers provided lower glare ratings than younger drivers at distances beyond 30 ft. Examination of the data by subject showed no outlier effects, suggesting that the current results are very likely to be repeatable and are therefore considered to be reliable.

Hartmann, E. (1970). *State-of-the-art driver vision requirements* (Paper No. 700392). New York: SAE.

The motorist assimilates more than 90% of the information he requires when driving in traffic via the visual system. For this reason, we must make every effort to facilitate the visual information process for the motorist. By this we mean primarily the geometric vision and corresponding tests have been arranged. Many problems arise if it is desired to determine the visibility conditions necessary for the motorist. The scientist is generally confronted with a multitude of uncoordinated data and test results which he has to sight. Moreover, the data, especially those gathered in driving tests on the road, are often based on a much too small number of test personnel to be really representative of the everyday motorist. The obvious idea of analyzing accident reports is similarly not suitable as the reports generally do not contain the desired particulars or only in an incomplete form.

Helder, D. J. (1987). *Design parameters for an automotive interior mirror* (Paper No. 870635). Warrendale, PA: SAE.

This paper presents a review of the work which has been done on determining appropriate automotive mirror reflectivity levels for good vision as well as glare protection. In addition, it presents the results of two recent studies on the effects of glare on driver vision. In the first, the level is determined at which glare from an interior mirror degrades the driver's forward vision. Four different ambient conditions are included. The second study looks at the effect of mirror transition time on discomfort and disability due to glare. Several current mirror systems are compared to the recommended parameters.

Helder, D. J. (1991). *Large-area variable reflectance mirrors for truck and buses* (Paper No. 912705). Warrendale, PA: SAE.

Glare from the headlights of following vehicles which is reflected in rearview mirrors can be a significant problem. Glare can cause driver discomfort, it can diminish the driver's ability to see, and it can cause driver fatigue, particularly during prolonged night-time driving common for many professional drivers. Conventional rearview mirrors, such as silvered and chromed mirrors, offer only one reflectivity level. Variable reflectance mirrors, such as those utilizing electrochromatic and liquid crystal technology, are capable of multiple reflectance levels. With variable reflectance, the driver can select a high reflectivity level during daytime driving or when reversing into loading docks, and can select a reduced dimmer reflectance level when driving during glaring conditions. This paper briefly reviews the principal technologies available for variable reflectance mirrors and outlines their performance as glare-reducing mirrors.

Helder, D. J. (1998). *Measuring curvature of mirrors using image analysis* (Paper No. 980917). Detroit, MI: SAE.
This paper describes a method for measuring the radius of curvature of mirrors by measuring the size of the reflected image. The image is generated by a video camera, captured using an image grabber board and analyzed using customer software on a standard computer. The system is shown to be capable to higher resolution than the current SAE-defined spherometer and capable of determining radius of curvature over a smaller area. The latter is particularly important in using the system for measuring aspheric mirrors.

Helmers, G., Flannagan, M. J., Sivak, M., Owens, D. A., Battle, D., & Sato, T. (1992). *Response times using flat, convex, and multiradius rearview mirrors* (Report No. UMTRI-92-20). Ann Arbor, MI: University of Michigan Transportation Research Institute.
This laboratory study evaluated the effect of three types of driver-side, exterior mirrors on drivers' response times for detection of cars at near distances in the left adjacent lane. The mirrors were a flat mirror, a convex mirror, and a multiradius mirror. All mirrors were of the same size and reflectivity. The drivers' visual field in the mirrors extended diagonally to the left about 20 deg for the flat mirror, 28 deg for the convex mirror, and 40 deg for the multiradius mirror. Consequently, there was a large blind spot using the flat mirror, a smaller blind spot using the convex mirror, but no blind spot using the multiradius mirror.

The primary task was to respond as quickly as possible to the presence or absence of a car in a photograph projected on a large screen behind the subject. (A secondary, loading task involved compensatory tracking.) The subjects responded by pushing one of two response buttons, depending on the presence or absence of the car. Time was measured from the onset of the photograph's appearance to the subject's response.

The main result is that the response times were shortest when using the multiradius mirror and longest when using the flat mirror. This was the case for younger and older subjects, as well as for American and Swedish subjects.

Kaehn, C. H. (1975). *Evaluation of two convex mirror systems by government drivers* (Report No. 750472). Warrendale, PA: SAE.
A nationwide field study of two types of convex mirror systems was made by the National Highway Traffic Safety Administration (NHTSA) with the cooperation of the General Services Administration (GSA) for a 10-month period starting in January 1974. One convex mirror system, called the Type I system, consisted of a non-adjustable convex mirror on the right fender, the original outside mirror on the driver's door, and a larger inside mirror. The Type II

mirror system consisted of an adjustable convex mirror mounted on each fender and the original inside rearview mirror.

A total of 515 Federal employees evaluated these two convex mirror systems at six major test locations to provide 627 questionnaires. An analysis of the questionnaires shows that drivers preferred the Type II convex mirror system over the Type I. From comments received, it seems that the drivers objected mostly to the non-adjustable feature and restricted field of view of the Type I system rather than to the fact that it was only a one-convex mirror system as compared to a two-convex mirror system. However, neither convex mirror system was rated as highly as the periscope system was evaluated in a previous field test of 50 periscope equipped GSA automobiles. This suggests that drivers would prefer unit magnification mirror systems with larger rearward fields of view over convex mirror systems with roughly the same view; nevertheless, drivers also prefer the convex mirror systems tested over conventional mirror systems because the convex mirrors provide greater rearward visibility

Kaehn, C. H. (1976). *Evaluation of a new automotive plane and convex mirror system by government drivers* (Paper No. 760006). Warrendale, PA: SAE.
An on-the-road study was made by the National Highway Traffic Safety Administration (NHTSA) with the cooperation of the General Services Administration of a new mirror system consisting of larger inside and left side plane mirrors and a convex mirror on the right fender. Approximately 150 Federal drivers evaluated this experimental mirror system on a test fleet of 23 passenger cars located at four sites for a six month period starting in September 1974. An analysis of the questionnaires completed by the drivers shows that in general drivers reacted favorably to this experimental convex mirror system. Comparisons are made with the results of earlier field tests conducted with a periscopic device and with two different experimental convex mirror systems.

Kesler, R. B., & Hufstedler, L. (1994). *Improving the field of view and the frame of reference in left and right rear view mirrors for passenger motor vehicles* (Paper No. 940645). Warrendale, PA: SAE.
There have been many attempts to improve rear vision for drivers of passenger vehicles, including but not limited to the following: Periscope mirrors -- Fiber optics -- Fresnel Lenses -- variable radius mirrors, which are used to some extent in Europe but have not been approved in the United States -- Electronic devices such as TV Camera/monitor -- infrared mini-radar -- photo cells and video micro chips. Many of these devices depend on electrical power to even be operational, and all of these devices have proved to be expensive as well as impractical and don't hold any promise for the near-term future.

Lee, S. E., Olsen, E. C. B., & Wierwille, W. W. (2004). *A comprehensive examination of naturalistic lane-changes* (No. DOT HS 809 702). Washington, DC: U. S. Department of Transportation National Highway Traffic Safety Administration.
This research effort provided valuable insight into the nature and severity of lane changes in a naturalistic driving environment. Sixteen commuters who normally drove more than 25 miles (40 km) in each direction participated. The two research vehicles were a sedan and an SUV; each participant drove each vehicle for ten days. Data gathering was automatic, and no experimenter was present in the vehicle. There were 8,667 lane changes observed over 23,949 miles of

driving, making this the largest known data collection effort for the study of lane changes. Analysis of the full data set resulted in many interesting findings regarding the frequency, duration, urgency, and severity of lane changes in regard to maneuver type, direction, and other classification variables. A subset of the full data set (500 lane changes) was then analyzed in greater depth using the sensor data collected by the instrumented vehicle. The sampled lane changes were generally of the more severe and urgent types since these are the cases in which a lane change collision avoidance system is likely to be of greatest help. Variables analyzed for the sampled lane changes included turn signal use, braking behavior, steering behavior, eye-glance patterns, and forward and rearward area analysis. The concept of a safety envelope for lane changes was then developed using the forward and rearward area analyses. Finally, the data were used to provide recommendations for designers of lane change CAS in terms of display location and activation criteria. Overall, the research described in this report provides insight into the behaviors and parameters associated with lane changes, while the naturalistic data archive has the potential to address other questions related to driving behavior.

Lockhart, T. E., & Atsumi, B. (2004). *Effects of planar and nonplanar driver-side mirrors on subjective discomfort-glare responses among young and old* (Paper No. 2004-01-1092). Warrendale, PA: SAE.

In this study, we evaluated subjective nighttime discomfort-glare responds on three different types of planar and non-planar driver-side mirrors on two age groups. Fifty-six individuals (28 young [18-35 years] and 28 old [65 years and over]) participated in this experiment. Subjective discomfort-glare rating scores on three different types of driver-side mirrors were assessed utilizing De Boer's rating scale in a controlled nighttime driving environment (laboratory ambient illuminant level - l lux with headlight turned off). Three driver-side mirrors included: planar ("flat mirror" - reflectance ratio of 39.12%) and nonplanar ("curved mirror" - reflectance ratio of 8.78% and "blue mirror" - reflectance ratio of 7.77%; R=1400 mm). The results indicated that with the same glare level (as measured by angle of incidence and illuminance on the front of the eyes), older adults reported lower De Boer's rating scores (i.e., worse feelings of glare) than their younger counterparts. Furthermore, the results indicated that both young and older adults reported lower De Boer's rating scores (i.e., worse feelings of glare) for planar driver-side mirror than non-planar driver-side mirrors. These results suggest that older adults' criterion of discomfort-glare is more sensitive than their younger counterparts, and importantly, the non-planar driver-side mirrors can be beneficial in terms of reducing nighttime discomfort-glare for both the young and the elderly.

Luoma, J., Flannagan, M. J., & Sivak, M. (2000). *Effects of nonplanar driver-side mirrors on lane change crashes* (Report No. UMTRI-2000-26). Ann Arbor, MI: The University of Michigan Transportation Research Institute.

This quasi-experiment investigated the effects on lane change crashes of nonplanar (spherical convex and multiradius) driver-side mirrors compared to planar mirrors. The analysis was based on 1,062 crashes reported from 1987 to 1998 to Finnish insurance companies, for vehicles with passenger-side spherical convex mirrors and one of three types of driver-side mirror (planar, spherical convex, or multiradius).

The results show that the mean effect of nonplanar mirrors compared to planar mirrors was a statistically significant decrease of 22.9% in lane-change crashes to the driver side. The effects of spherical convex and multiradius mirrors were not statistically different from each other. The nonplanar mirrors were beneficial especially for the high-risk driver groups, as well as for the lane-change situations and environmental conditions in which most lane-change crashes take place in the United States.

The present findings support the use of nonplanar driver-side mirrors. If drivers have problems with judgments of the speed and distance of approaching vehicles using nonplanar mirrors, the magnitude of this concern seems to be minimal compared to apparent benefits with regard to other mechanisms of lane-change crashes.

Luoma, J., Sivak, M., & Flannagan, M. J. (1994). *Effects of driver-side mirror type on lane-change accidents* (Report No. UMTRI-94-34). Ann Arbor, MI: The University of Michigan Transportation Institute.

This quasi-experiment was designed to investigate the effects of the type of driver-side mirror on lane-change accidents. The analysis was based on 407 accidents reported from 1987 to 1992 to Finnish insurance companies, for vehicles with passenger-side convex mirrors and one of three types of driver-side minors (flat, convex, or multiradius).

The results showed that there was no difference between the multiradius and convex minors in the frequencies of lane-change accidents to the left. Compared to the flat mirror, the mean effect of the multiradius and convex mirror was a 22% decrease. The 95% confidence interval ranged from a 51% decrease to a 25% increase. This result was not related to driver characteristics or driving conditions.

In conclusion, the multiradius and convex driver-side mirrors, in comparison to the flat mirror, are more likely to reduce than increase lane-change accidents. A theoretical implication of this study is that minimizing the blind spot is likely to be more important than providing an undistorted image of objects. From a practical point of view, the present findings support the use of multiradius and convex driver-side mirrors.

Luoma, J., Sivak, M., & Flannagan, M. J. (1995). Effects of driver-side mirror type on lane-change accidents. *Ergonomics, 38*(10), 1973-1978.

This quasi-experiment was designed to investigate the effects of the type of driver-side mirror on lane-change accidents. The analysis was based on 407 accidents reported from 1987 to 1992 to Finnish insurance companies, for vehicles with passenger-side convex mirrors and one of three types of driver-side minors (flat, convex, or multiradius).

The results showed that there was no difference between the multiradius and convex mirrors in the frequencies of lane-change accidents to the left. Compared to the flat mirror, the mean effect of the multiradius and convex mirror was a 22% decrease. The 95% confidence interval ranged from a 51% decrease to a 25% increase. This result was not related to driver characteristics or driving conditions.

In conclusion, the multiradius and convex driver-side mirrors, in comparison to the flat mirror, are more likely to reduce than increase lane-change accidents. A theoretical implication of this study is that minimizing the blind spot is likely to be more important than providing an

undistorted image of objects. From a practical point of view, the present findings support the use of multiradius and convex driver-side mirrors.

Mortimer, R. G. (1971). *The effects of convex exterior mirrors on lane-changing and passing performance of drivers* (Paper No. SAE 710543). New York: SAE.
Drivers carried out a lane-changing and passing maneuver using convex and plane exterior mirrors alone or in combination with a plane interior mirror. The data showed that the addition of the plane interior mirror compensated for judgmental errors found when convex mirrors were used alone. When the speed difference was 15 mph between the overtaking car and the subject's car, subjects accepted gaps that were too short irrespective of the exterior mirror type. The data suggested that exterior convex mirrors of radii greater than 30 in. may be used reasonably safely by drivers and would have the advantage of providing a considerably increased field-of-view compared to currently used exterior mirrors.

Mortimer, R. G., & Jorgeson, C. M. (1974). *Drivers' vision and performance with convex exterior rearview mirrors* (Paper No. 740961). Warrendale, PA: SAE.
A laboratory simulation of dawn/dusk illumination showed that following vehicles could be detected equally well in plane and convex mirrors, and a night driving test showed that low- and mid-beam headlamps of a following car produced discomfort glare responses that were independent of whether the exterior mirror was plane or convex. Visibility of the following car was rated better with the plane exterior mirror. Measures of performance of drivers relevant to safety in lane changing and passing were not different when they used a plane or convex exterior mirror in conjunction with a plane interior mirror, and did not differ in the day or at night. When the initial speed of the overtaking car was 15 mph (24 km/h) greater than the subjects' car, drivers significantly underestimated the relative speed, indicating a potential cause of collisions with a following vehicle in lane changing and passing maneuvers.

Mortimer, R. G., & VanderMey, T. J. (1971). Analysis of collisions involving rear vision. *Hit Lab Reports*, 4-5.
The proportion and severity of accidents believed to involve rear vision were analyzed. The data were taken from Michigan's Oakland and Washtenaw counties. In these counties, respectively, less than 3.0% and 1.4% of all two-or-more-vehicle collisions involved rear vision; the severity of these collisions was less than the average of the other two-or-more-vehicle collisions. We conclude that these rear-vision collisions may be reduced by improving the field of view to the rear, particularly the right rear. Low-cost methods, such as convex mirrors, seem to be warranted based on the accident analysis and on experimental studies.

Mourant, R. R., & DeNald, R. E. (1974, October 1974). The effects of age and visual capability on performance with plane and convex mirrors. *Proceedings of the Human Factors Society, 18*, 123-128.
Reaction times were measured for a detection task and a recognition task when using plane mirrors and when using convex mirrors. Three groups of nine drivers each (Young, Mature-with Bifocals, and Mature-No Glasses) were studied. The detection task consisted of reporting the number of Landolt Rings. (0,1,2,3, or 4) that were made to appear in a mirror. The recognition task consisted of reporting the orientation (left, right, up, or down) of the Landolt Ring gaps. On both the detection and recognition tasks differences between types of subjects increased as the

convexity of the mirror increased. The largest differences occurred when the images were displayed in a 40 inch convex mirror. Here, Mature-No Glasses subjects took .77 seconds longer to report target orientation than Young subjects. On the same task, Mature-Bifocaled subjects took only 0.18 seconds longer than the Young subjects. Since the longer reaction times of Mature-No Glasses subjects appears to be due to their poorer visual acuity it is recommended that states require higher visual standards with respect to far visual acuity.

Mourant, R. R., & Donohue, R. J. (1974). ***Mirror sampling characteristics of drivers*** **(Paper No. 740964). Warrendale, PA: SAE.**
Driver behavior in obtaining information through rearview mirrors and head turns was analyzed for novice, young experienced, and mature drivers during daytime driving on a freeway route. No significantly different mirror sampling patterns were obtained when the horizontal fields of view of the plane left side and inside mirrors were expanded by approximately 25%. Some difference in behavior did occur between the mature and the other drivers, especially in mirror use when driving straight ahead. The total time to obtain information for left merges was significantly larger than for left and right lane changes and a right merge. Finally, the time required to obtain information to make a decision for a left or right lane change without execution was considerably less than the time needed when the maneuver was actually executed.

Mourant, R. R., & Donohue, R. J. (1977). Acquisition of indirect vision information by novice, experienced, and mature drivers. ***Journal of Safety Research, 9*****(1), 39-46.**
Driver behavior in obtaining information through rearview mirrors and direct looks to the rear scene was recorded for four vehicle mirror systems. Three novice, three young experienced, and three mature drivers drove each vehicle mirror system once on a freeway route and once on a city route. Driver glance behavior, as well as the road scene in front of and in back of the vehicle, were recorded by television cameras. When drivers simply drove straight ahead, the amount of time spent sampling the vehicle's left side mirror and a fender-mounted convex mirror appeared to be a function of the amount of driving experience. Novice drivers and young experienced drivers made fewer glances to the left outside mirror and convex mirror than did mature drivers. When gathering information prior to executing maneuvers (lane changes and merges), novice drivers made direct looks in place of using the vehicle's mirrors. Mirror glance duration was found to be independent of the amount of driving experience. It is recommended that methods be developed to teach better mirror use habits in driver education curricula.

Mourant, R. R., & Donohue, R. J. (1979). Driver performance with right-side convex mirrors. ***Transportation Research Record, 737*****, 95-100.**
The mirror-use behavior of drivers was investigated as they gathered information from rearview mirrors in order to execute freeway lane changes and merges. Nine drivers (three novice, three experienced, and three mature) drove a 1973 Buick LeSabre with and without a right-side fender-mounted convex mirror along a 22.5-km (14-mile) freeway route. The total time to obtain information per maneuver was the same for both cases. In a subsequent study, the mirror-use behavior of five subjects who drove a 1976 Nova without a right-side convex mirror was compared with that of 12 subjects who drove the same vehicle with a right-side door-mounted convex mirror. Again there were no differences in total time to obtain rear-vision information. Experienced drivers (mean age = 24) took less time to obtain information when a right-side convex mirror was available than when it was not; older drivers (mean age = 61) took more time.

Also, experienced drivers required about 10 h of driving experience to become efficient users of a right-side convex mirror, while older drivers required considerably more driving experience. Finally, a comparison of right-side door- and fender-mounted convex mirrors indicated that the drivers' total time to obtain information was the same for each mounting location, but drivers who had the fender-mounted mirror made a greater number of direct looks to the rear.

Mourant, R. R., & Rockwell, T. H. (1972). Strategies of visual search by novice and experienced drivers. *Human Factors, 14*(4), 325-335.

Six novice drivers drove a 2.1-mi. neighborhood route and a 4.3-mi. freeway route. Eye movements (including blinks and glances to the vehicle's mirrors and speedometer) were videotaped. The visual behavior of a control group, consisting of four experienced drivers, was also videotaped on the same routes. The results showed that the novice drivers: (1) concentrated their eye fixations in a smaller area as they gained driving experience, (2) looked closer in front of the vehicle and more to the right of the vehicle's direction of travel than the experienced drivers, (3) sampled their mirrors less frequently than the experienced drivers, and (4) made pursuit eye movements on the freeway route while the experienced drivers made only eye fixations. These results suggest that the visual acquisition process of the novice drivers was unskilled and overloaded. Thus, the search and scan patterns of the novice drivers may be considered unsafe in terms of impairing the drivers' ability to detect circumstances that have high accident potential. On this basis it is recommended that novice drivers be prohibited from driving on public roads until they achieve an acceptable level of vehicle handling control and develop skill in acquiring visual information.

O'Day, S. M. (1998). *Binocular disparity in aspherical mirrors* (Paper No. 980918). Warrendale, PA: SAE.

An aspherical mirror is a convex spherical mirror whose radius of curvature decreases as the line of sight moves horizontally on the mirror from inboard to outboard. This differs from a regular spherical convex mirror which has the same radius of the curvature everywhere on the mirror. Aspherical mirrors provide an increased field of view and larger images sizes than would be possible with a traditional spherical convex mirror. One potential concern with aspherical mirrors is binocular image disparity. Binocular image disparity in an aspherical mirror results from the situation where one eye sees an image on a portion of the mirror with a larger radius of curvature than the other eye sees. The differences in image sizes can cause discomfort to the person using the mirror and, if the difference is large enough, the person sees a double image. This paper describes a method for quantifying the binocular image disparity in aspherical mirrors. The method involves measuring images in the mirror in angular degrees with respect to the driver's eye. Binocular Image Disparity is defined as the percent change in angular image size seen by the driver's right eye versus left eye. Four types of targets were used to measure disparity: vertical linear and horizontal linear (one-dimensional) targets, area (two-dimensional) targets and volume (three-dimensional) targets. Three eye-to-target distances were analyzed: 2000 mm, 4000 mm and 6000 mm. Four aspherical mirrors were analyzed. This method characterizes aspherical mirrors in terms of the maximum binocular image disparity and the maximum rate of change in binocular image disparity. Binocular image disparity was largely unaffected by target distance. The square area target was recommended over the other target types

Pilhall, S. (1981). *Improved rearward view* (Paper No. 810759). Warrendale, PA: SAE.
Various possibilities to improve the rearward view in passenger cars have been studied, with the aim, among others, to eliminate "dead angle". Tests have been performed with periscopes, vehicle TV, combined mirrors and mirrors with continuously variable curvature. The later ones have been optimized to a well functioning solution.

Platzer, G. (1995). *The geometry of automotive rearview mirrors - Why blind zones exist and strategies to overcome them* (Paper No. 950601). Warrendale, PA: SAE.
Equations are derived which describe and relate the magnification, viewing angle and reflected illuminance of convex mirrors as used in automotive applications. The derived equations are compared to those for plane mirrors. Using these equations, the viewing angles of automotive rearview mirrors are calculated and depicted. The blind zones are defined in terms of the viewing angles, obstructions to vision, perceptibility limitations, and the lateral separation of vehicles. Various strategies for overcoming the blind zones are discussed.

Reed, M. P., Lehto, M. M., & Flannagan, M. J. (2000). *Field of view in passenger car mirrors* (Report No. UMTRI-2000-23). Ann Arbor, MI: University of Michigan Transportation Research Institute.
Mirror fields of view (FOV) of 43 men and women were measured in their own passenger cars. A manual pole-sighting method was supplemented by calculations from three-dimensional vehicle data. A coordinate measurement machine was used to record the mirror orientations and driver eye locations. The mean horizontal FOV widths were 12.9, 25.3, and 22.5 degrees for the left (driver-side), center, and right mirrors, respectively. On average, drivers could see 14.0 degrees outboard on the left and 19.8 degrees outboard on the right. Driver age, gender, and body size did not significantly affect mirror aim. The vehicle defined the edge of the horizontal FOV in the left and right mirrors for 84% and 78% of drivers in the left and right mirrors, respectively. On average, the vehicle took up 21% of the available horizontal FOV in the left mirror. FOV were not significantly different after the drivers were allowed to reaim the mirrors, except that the outer edge of the left mirror horizontal FOV increased to 15.1 degrees outboard. The distributions of mirror FOV parameters were comparable to those reported in an earlier study, but the current data are much more detailed and include the physical mirror orientation, mirror dimensions, mirror positions relative to driver eye location, and other information. Summary statistics on the parameter distributions are provided to facilitate modeling of mirror FOV.

Robinson, G. H., Erickson, D. J., Thurston, G. L., & Clark, R. L. (1972). Visual search by automobile drivers. *Human Factors, 14*(4), 315-323.
Data are presented on the visual search of automobile drivers during two maneuvers: (1) entering a highway after a stop, and (2) changing lanes on a multilane highway. Head-movement measurements were used to infer patterns and timing of search. The relationships between eye and head movements are discussed.

Rogers, R. (1989). *Vehicle design and older drivers*. Chicago, IL: National Safety Council.
The Highway Safety Forum decided that there were several avenues open within the automotive design process that could address older drivers and their needs, primarily within the areas of vision and occupant protection and somewhat in cognition. Some controls and displays certainly could provide increased benefits if they are designed to be larger, more readable and less

cluttered, and assisted, where necessary, by audible warnings. More simplified control systems also could be of assistance to this population.

Since mature drivers are over represented in side impact accidents, Forum members supported the high priority that safety engineers are placing on resolving occupant protection issues associated with such impacts. Safety engineers are urged to use mature drivers as a basis for developing design criteria due to their lesser tolerance to impact injury and their higher intersection accident frequency. This approach should lead to greater improvements compared to designing toward healthy young persons.

Since mature persons also tend to curtail their driving at night because of a heightened sensitivity to glare and a need for more road seeing distance, members suggested improved lighting. Exploring such concepts as mid-beam head lamps, glare reduction by controlling truck head lamp heights and wider use of automatic head lamp dimmers were suggested.

Finally, the members expressed a strong desire for increased dialogue between manufacturers, the medical community, law enforcement and insurance agencies, and the setting up of some mechanism for bringing together the different disciplines they represent.

Rowland, G. E., Silver, C. A., Volinsky, S. C., Behrman, J. S., Nichols, N. F., & Clisham Jr., W. F. (1970). ***A comparison of plane and convex rearview mirrors for passenger automobiles*** **(No. DOT HS-800 396). Washington D.C.: National Highway Traffic Safety Administration.**

Plane and convex mirrors were compared. Experiments were performed on the effects of various convexities in relation to eye/mirror geometry, eye anomalies, time of day, mirror size, learning required to use convex mirrors, and the use of combination mirrors. Data are given for judgments in spatial localization and detection probabilities for a wide range of interior passenger-carrying buses: (3) the nonutilization of convex mirrors provide an improved probability of detecting other automobiles while providing accurate spatial localization. Convex mirrors of about 40-inch radius appear to be a satisfactory compromise in terms of convexity. It is recommended that 40-inch convex mirrors be installed on left and right front fender areas and in the upper center of the windshield of all passenger cars. Further research is recommended. A new safety standard for rearview mirrors is suggested.

Schumann, J., Sivak, M., & Flannagan, M. J. (1996). ***Are driver-side convex mirrors helpful or harmful?*** **(Report No. UMTRI-96-7). Ann Arbor, MI: The University of Michigan Transportation Research Institute.**

This analysis of accident data was designed to replicate and extend an earlier analysis that investigated the effects of different types of driver-side mirrors on lane-change accidents (Luoma, Sivak, and Flannagan, 1995). The present analysis was based on 3,038 lane-change accidents that occurred in Great Britain between 1989 and 1992. Mirror information for the most popular car models in Great Britain was collected to identify different types of exterior mirrors. Data analysis was based on the odds ratio of cars with different types of driver-side mirrors (plane or convex) being involved in a lane-change accident to the driver side. Because all cars were equipped with the same type of passenger-side mirror (convex), lane-change accidents to the passenger side served as baseline data to control for exposure. The results can be summarized

as follows: (1) Convex driver-side mirrors do not increase the risk of being involved in lane-change accidents to the driver side; (2) Consistent with the findings of Luoma et al. (1995), accident data for the largest cars revealed a tendency, albeit not statistically significant, for a decrease in lane-change accidents to the driver side when equipped with convex driver-side mirrors; and (3) Convex driver-side mirrors tended to be beneficial for the highest risk groups--the youngest and the oldest drivers.

Seashore, C. G., & Lundquist, E. C. (1968). *The scientific application of optics and accident prevention to mirror vision for commercial drivers* (Paper No. 680107). New York, NY: SAE.
To the average truck or bus driver the critical problem of the "blind spot" has existed ever since flat mirrors were first applied to vehicles. With large vehicles and the single plane mirror it is entirely possible for a car to be hidden under the driver's lower line of vision. This problem of "blind spot" is compounded, depending on the size of the vehicle, driver's eye level above the ground, and the distance and position of his eyes from the mirrors.

The mathematically designed mirrors discussed in the paper permit the driver to utilize the upper flat mirror for rearward vision; the reflected view of the blind area is in the bottom prepositioned mirror. It is believed that the next area of optics improvement will be with the noncommercial driver

Seeser, J. W. (1976). *Automotive mirror size requirements based on field of view considerations* (Paper No. 760005). Warrendale, PA: SAE.
The results of a two mirror computer model of automotive rear vision based on a minimum field of view approach are presented. A system of conventions for the rear vision target, minimum field of view, head positioning, mirror orientation, and head rotation is used to parameterize computer results in terms of the position of the center of the inside mirror and the left outside mirror. General results for the minimum horizontal mirror size and driver head turn required to see the target are presented. Superimposed on the results are several existing automotive models.

A sensitivity analysis is performed to indicate the sensitivity mirror size to various parameters in the model. The results indicate that the mirror size is particularly dependent on the transverse eye-mirror distance.

Shinar, D., & Schieber, F. (1991). Visual requirements for safety and mobility of older drivers. *Human Factors, 33*(5), 507-519.
Efforts to assess visual deterioration with increasing age, coupled with new mechanisms proposed to limit the exposure of visually impaired drivers to driving risks, have emerged in response to the increase in older drivers. Visual functions discussed in this context include static acuity (photopic, mesopoic, and in the presence of glare), dynamic visual acuity, visual field, contrast sensitivity, and motion perception. Exposure control mechanisms discussed include alternative periodic vision testing strategies, visual training, and environmental and vehicular modifications to accommodate the older driver. Finally, relevant research needs are addressed.

Sivak, M., Devonshire, J., Flannagan, M. J., & Reed, M. P. (2008). *Mirror size and lane-change crashes* (Report No. UMTRI-2008-32). Ann Arbor, MI: The University of

Michigan Transportation Research Institute.
This study examined the relationship between the size of the driver-side outside mirror and the frequency of lane-change crashes. To control for other vehicle and driver differences that might be associated with mirror size, the frequency of going-straight-ahead crashes was used for comparison. The analysis used 1991-2005 North Carolina crash data. The sample consisted of 77 vehicles, including 37 passenger cars, 14 minivans, 14 SUVs, and 12 pickup trucks. The physical dimensions of the vehicles' mirrors were measured with respect to a three-dimensional coordinate system that was relative to fixed points on the ground, when the driver was sitting in his/her normal driving position and looking at the mirror. Eye locations measured while drivers looked in the mirror were used to calculate the nominal field of view provided by the mirror. The effective field of view, limited by the body structure of the vehicle, was obtained using a manual pole-sighting technique.

The main finding is that the relative likelihood of lane-change crashes was not related to the width, the height, or the area of the driver-side mirror. The most likely reason for this finding is that the effective field of view was not related to mirror size (although the nominal field of view was). That, in turn, is partly a consequence of two trends: larger mirrors being associated with larger eye-to-mirror distances, and drivers aiming their mirrors in ways that do not take full advantage of larger mirror sizes.

Smith, R. L., Bardales, M. C., & Burger, W. J. (1978). *Perceived importance of zones surrounding a vehicle and learning to use a convex mirror effectively* (No. DOT-HS-803 713). Washington, D.C.: U.S. Department of Transportation.
The study investigated the effects of training on judgments of vehicle distances and speeds as viewed through a 50-inch convex mirror. Subjects varying in age and driving experience were given 192 trials over four test sessions. In general, all groups showed substantial learning over test sessions and within-group variability also decreased markedly. The most superior performing group, one having several years of convex mirror usage, produced more accurate judgments than a control group which viewed the vehicle images on plane mirrors.

Staplin, L., Lococo, K., Sim, J. J., & Gish, K. (1998). *Simulator-based assessment of driver-side mirrors for passenger cars* (No. DOT HS 808 807). Washington, DC: U.S. Department of Transportation.
This report describes an empirical study comparing four alternative driver's side rear view mirror designs to a standard planar mirror. Primary study variables were field-of-view size and image distortion, plus driver age. In a repeated-measures design, subjects in a laboratory driving simulator used each mirror type from the perspective of a stationary observer waiting to merge, and as moving observers in a dynamic simulation of a lane-change scenario on a freeway. Subjective measures of user acceptance of the alternative mirror designs were also obtained in a controlled field setting. The results found significant effects of mirror type and driver age on lane change decisions and decision times.

Sugiura, S., & Kimura, K. (1978). *Outside rearview mirror requirements for passenger cars - curvature, size, and location* (Paper No. 780339). Warrendale, Pennsylvania: SAE.
Primary design factors with regard to outside mirrors are curvature, size and spatial localization. Experiments were conducted to find the effects of these factors in relation to visibility and the

size of field of view. Investigations to determine visibility requirements were static testing and field testing. The results show that convex mirrors with 47 inch radius of curvature are most preferable for the visibility requirements. Required size of field of view was established taking into account the size of direct field, vehicle size and lateral distance to another car.

Swigart, T. F., & Farber, E. (1973). *Field of view from automotive vehicles* (Paper No. SP-381). New York: SAE.

This report presents the findings of Ford Motor Co. research on fields of view 360 deg around automotive vehicles. The research considered forward, side, and rear fields of view from forward-moving vehicles. Rear vision through mirror systems was included. No attempt, however, was made to define the fields of view of drivers who look to the rear through windows without the use of mirrors. The analysis of direct vision to the rear and backing maneuvers must be deferred until more is known about the eye locations of drivers when looking directly to the rear.

The research results presented in this report are described and illustrated for passenger cars. Technical issues and assumptions peculiar to vehicles other than passenger cars (that is, light trucks, MPV's, heavy trucks and buses) are treated in a separate section. Two-wheeled vehicles, off-road vehicles and specialized construction equipment are not considered. General descriptions of the driver's vision fields are given in the summary. Detailed presentations and explanations are given in the body of the report. Background material is provided in the Technical Notes.

Taoka, G. T. (1990). Duration of drivers' glances as mirrors and displays. *Institute of Transportation Engineers Journal, 60*(10), 35-39.

The frequency and duration of visual glances by drivers scanning the roadway scene has been researched. Recent studies have given statistical parameters of experimental data. This data allows the statistical distribution of driver glance times to be estimated based on an appropriate analytical model. This paper presents the statistical distribution of driver glance times to two mirrors, four dashboard displays, and an outside-the-vehicle target. The closeness with which the model approximates the data is presented in detail for one dashboard display. The details of the study are described, and the results are discussed.

Walraven, P. L., & Michon, J. A. (1969). *The influence of some side mirror parameters on the decisions of drivers* (Paper No. 690270). New York, NY: SAE.

General considerations about the use of convex mirrors indicate that they may be very useful to enlarge the field of view. There seems to be no need to use smaller values for the radius of the mirror than 1000 mm. A reaction time experiment is described in which plane mirrors of equal size at different positions on the fender are used. There are indications that the position of about 20 degrees out of the line of sight straight ahead might be optimal. Whether this also holds for convex mirrors is not investigated.

An experiment is described in which a driver must decide whether he can overtake a car in front of him, while a car behind him is approaching. This is done with several speeds of the car behind and with different curvatures of the side mirrors. Especially if the radius of curvature is not less than 1200 mm, no serious effects on driver behavior is observed. The instrumented car used in the studies is briefly described.

Wierwille, W. W., Schaudt, W. A., Gupta, S. K., Spaulding, J. M., Bowman, D. S., Wiegand, D. M., & Hanowski, R. J. (2008). Study of driver performance/acceptance using aspheric mirrors in light vehicle applications: Final report (No. DOT HS 810 959). Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration.

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 (E.U.), but not in the U.S., 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 on-line 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 twelve 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. 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.

Wu, B., Ooi, T. L., & He, Z. J. (2004). Perceiving distance accurately by a directional process of integration ground information. *Nature, 428,* 73-77.

By itself, the absolute distance of an object cannot be accurately judged beyond 2–3 m (refs 1–3). Yet, when it is viewed with reference to a flat terrain, humans accurately judge the absolute distance of the object up to 20 m, an ability that is important for various actions (4–8). Here we provide evidence that this is accomplished by integrating local patches of ground information into a global surface reference frame. We first show that restricting an observer's visual field of view to the local ground area around the target leads to distance underestimation, indicating that a relatively wide expanse of the ground surface is required for accurate distance judgment. Second, as proof of surface integration, we show that even with the restricted view, the observer can accurately judge absolute distance by scanning local patches of the ground surface, bit by bit, from near to far, but not in the reverse direction. This finding also reveals that the surface integration process uses the near-ground-surface information as a foundation for surface representation, and extrapolation to the far ground surface around the target for accurate absolute distance computation.

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